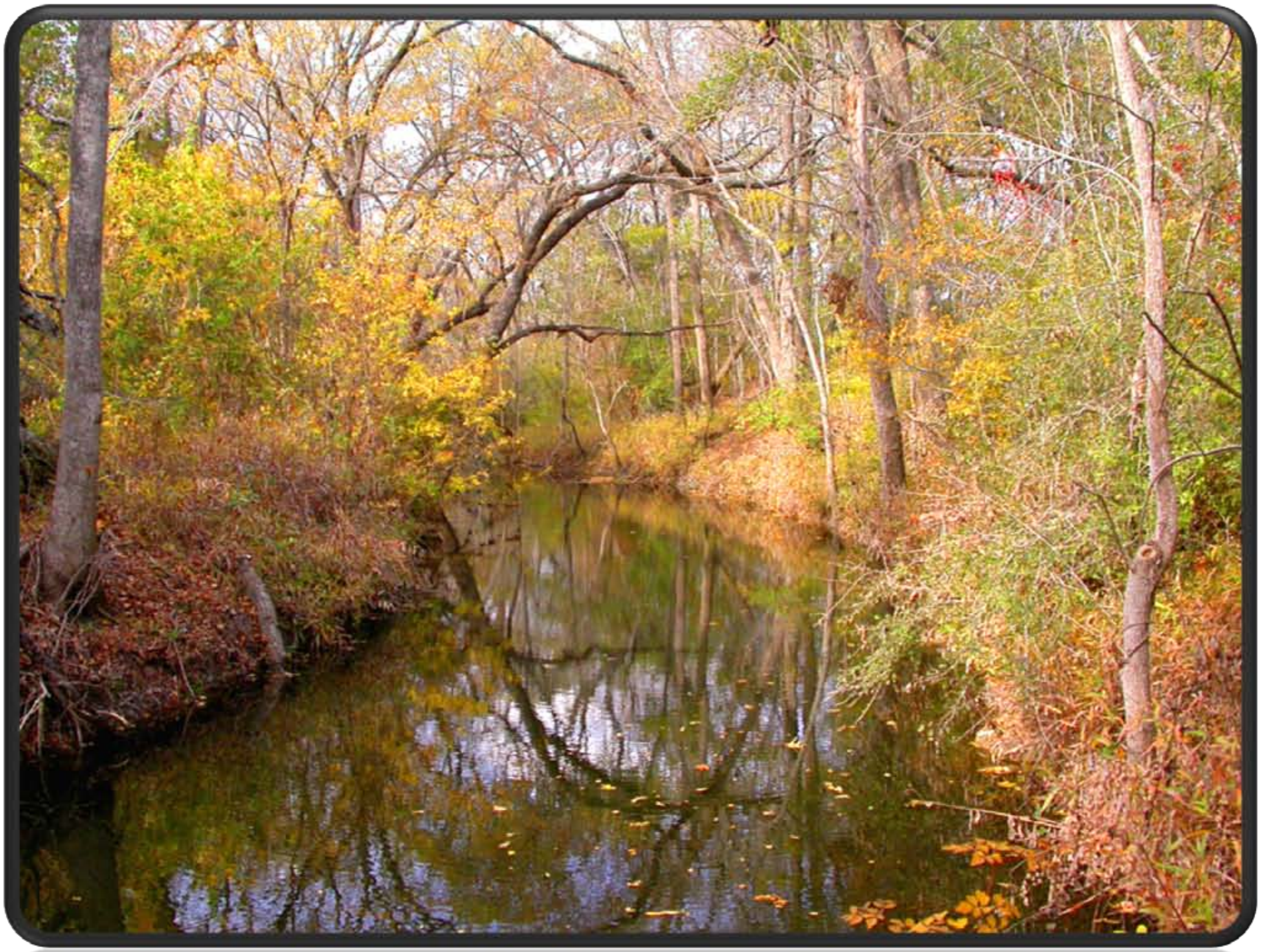

An Approach for Estimating Stream Health Using Flow Duration Curves and Indices of Hydrologic Alteration

March 2011

AgriLIFE RESEARCH & EXTENSION
Texas A&M System

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Protocol document for assessing stream health using stream flow duration curves and flow based hydrologic indices.

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Chapter 1: Introduction

Maintaining healthy streams can challenge city, county and state resource managers. Increased human population and land use change can lead to changes in overland flow processes and therefore stream flow. These changes may disrupt a stream's physical and chemical integrity thereby affecting the abundance and diversity of aquatic flora and fauna as well as overall water quality. At the same time, local, state and federal agencies must meet the demand to supply people with high quality water.

Many streams in the five states of EPA Region 6 are impaired. Water quality and physical habitat are degraded by changes in the hydrologic regime arising from land cover and land use changes, such as urbanization. These changes disrupt the watershed by modifying the stream's hydrologic characteristics resulting in changes to the magnitude, duration, and frequency of stream flow. From this stems a cascading effect on a variety of physiochemical characteristics such as dissolved oxygen, pH, temperature, turbidity, and sediment as well as the chemical content and biological characteristics (*i.e.*, aquatic plants and animal life) of water bodies. These hydrological changes are often accompanied by water quality degradation due to increased pollutant loading into streams.

Using water quality and biological criteria alone to restore impaired streams is insufficient due to the influence of changes in land cover and land use that hydrologically alters streams. Assigning a single-pollutant chemical water quality criterion is not the most effective method to achieve restoration or preserve stream features. Instead, stream restoration could be achieved by managing flow, which is the driver of stream health (Poff, Allen et al. 1997). Flow-stream ecology relationships determine the ecological conditions associated with stream flow.

This report describes a developed protocol for establishing stream flow-based goals to maintain or restore stream health. The approach uses statistical parameters of flow to estimate hydrologic alterations resulting from land cover change, urbanization, man-made structures, etc., over a period of time. This document provides step-by-step procedures for estimating stream health based on flow-ecology relationships using two Texas watershed case studies in EPA Region 6: White Rock Creek in Dallas County and Plum Creek in Hays and Caldwell Counties. For each case study, considerations and limitations in using the approach are presented.

Chapter 2: Basic Steps to Assess Stream Health from Flow Data

The protocol for assessing stream health using stream flow data follows an eight-step process (Figure 2.1). Stream flow is an essential requirement for estimating stream health. A stream flow database contains a time series of daily flow values obtained from monitored observations, estimated from a hydrologic simulation model, or estimated through statistically based estimation. The user needs to develop a stream flow database specific to the study area to estimate stream health (example shown in Chapter 4). After obtaining flow data, the hydrologic alterations must be identified. Hydrologic alterations are defined by an increase or decrease in flow trend(s) over time. Hydrologic alterations can result from land cover and land use changes, such as urbanization, climate change, or the creation of surface water impoundments in the stream or within the watershed. Hydrologic alterations for a study area can be estimated without the knowledge of changes in land cover, climate, or other man-made alterations to the landscape in the study area. However, any information on these will help to verify the period of hydrologic alteration obtained using this approach. Typically, stream health analysis involves comparing hydrologic indices taken from pre-alteration and post-alteration flow data periods. A pre-alteration period could represent past or current conditions, while the post-alteration period may represent current or future situations. The protocol described in this document follows this approach.

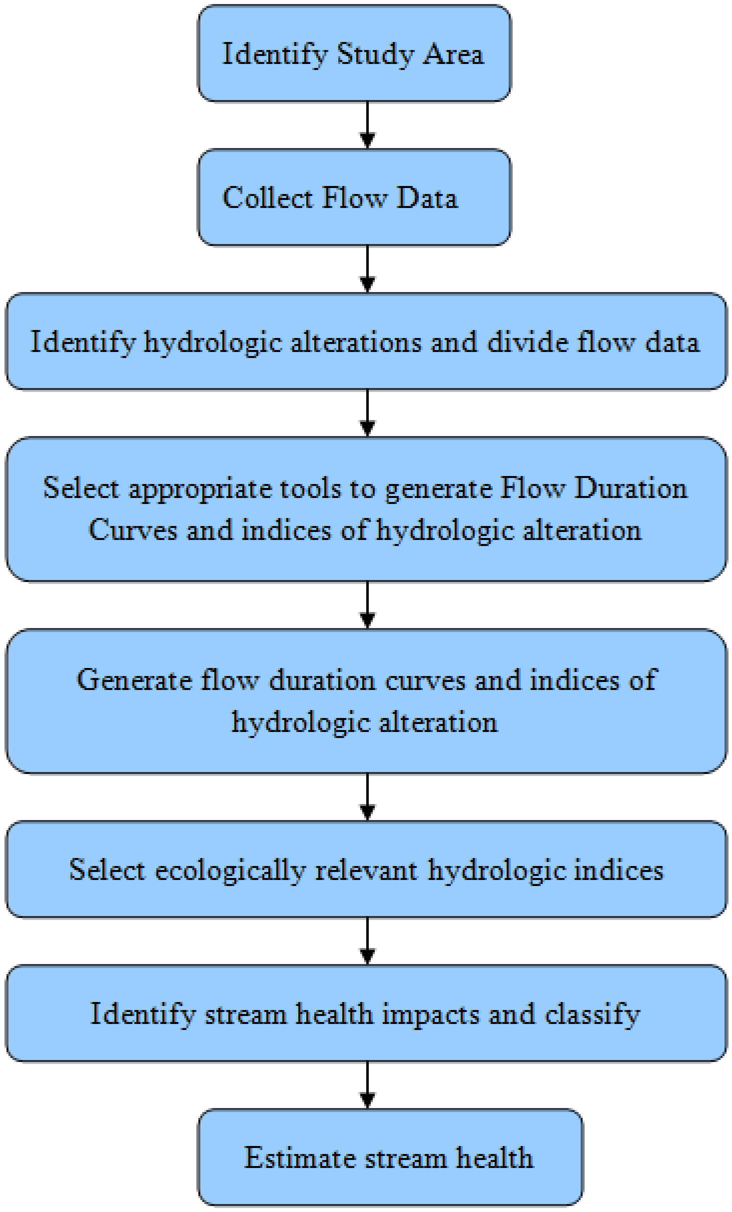

Figure 2.1: A Protocol for Estimating Stream Health from Flow Data

Characterizing stream health requires two components: stream flow data and a basic understanding of hydrologic characteristics associated with the stream or watershed of interest. The basic steps in the protocol are outlined in Figure 2.1. Detailed information regarding each step is given in chapters 3 through 9.

Chapter 3: Step 1 - Identify Assessment Area

To begin an assessment of stream health using flow data, one must first identify an assessment area of interest. This area may be a single reach or multiple river reaches where the stream health is expected to be altered by anthropogenic activities. Activities to consider include dam construction, stream bank vegetation removal, pumping or other abstractions, effluent discharge, and land cover and land use changes (*i.e.*, urbanization, etc.)

Assessment areas can be chosen based on existing water quality impairments. While choosing the assessment area, the restoration priorities of the agency or state should also be considered. Assessment areas can also be chosen based on a desire to better understand the stream flow of an area before other activities occur. This might involve several probable scenarios. While choosing assessment area the size of the watershed matters for obtaining flow data. When monitored observations are available for estimating stream health, the assessment can be limited to those reaches where data is available making the assessment easy, cost effective, and simple. On the other hand, if flow data has to be estimated using a modeling tool, the assessment reaches can be as many as desired. This will involve collection of elevation, soil, land cover, weather and land management data to setup the model for the watershed, and validate the model setup. Procedures to identify hydrologic changes are found in Chapter 5.

Chapter 4: Step 2 - Create a Stream Flow Database

After an assessment area is identified, it is necessary to collect stream flow data. These flow data can be obtained directly from stream monitoring gauges (Figure 4.1) or they can be estimated using a hydrologic simulation model (Figure 4.2).

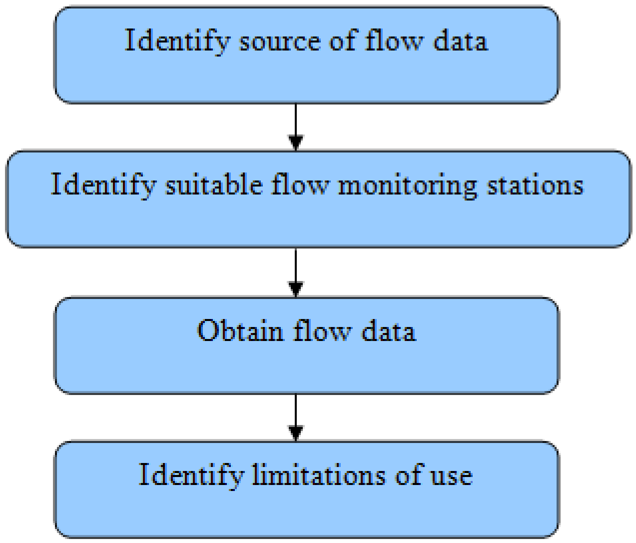

Figure 4.1: Protocol for Obtaining Data from Monitored Observations

A possible method using a simulation model such as Soil and Water Assessment Tool (SWAT) to estimate flow data is illustrated in Appendix C along with the case study for the White Rock Creek watershed. Alternatively, in un-gauged watersheds, the web-based USGS tool StreamStats may be used to estimate stream flow. It should be noted that Stream Stats is not yet available for all the EPA region 6 states.

The United States Geological Survey-National Water Information System (USGS-NWIS) is a major source of publicly available stream flow monitoring data for the nation (http://waterdata.usgs.gov/nwis). For EPA Region 6, the USGS-NWIS reports flow data for more than 2,000 locations using automatic loggers and manual samplers. USGS-NWIS reports real-time flow data from gages at three to four hour intervals. These data are initially posted on the United State Geological Survey (USGS) district home page as provisional data which have not been reviewed or edited. Data posted from each USGS station record are considered provisional until they are published in the USGS water data report (https://pubs.usgs.gov/wdr/). USGS reports summarize daily values for daily mean flow and peak flow. When adequate flow data are available, daily median, maximum, minimum, and other derived values are also posted.

Daily, monthly, and annual flow statistics are computed from approved daily mean time-series data at each site and published by USGS-NWIS at:

http://waterdata.usgs.gov/nwis/dv/?referred_module=sw. Data are listed by site location--(State/Territory, Hydrologic Region [a USGS river basin classification system] and Latitude-Longitude). Drainage area and data attributes such as number of observations and site identifiers, including site name, site number, and the sample collection agency code are also included in the site selection criteria. Additional information on obtaining USGS-NWIS flow data is provided in Appendix A1.

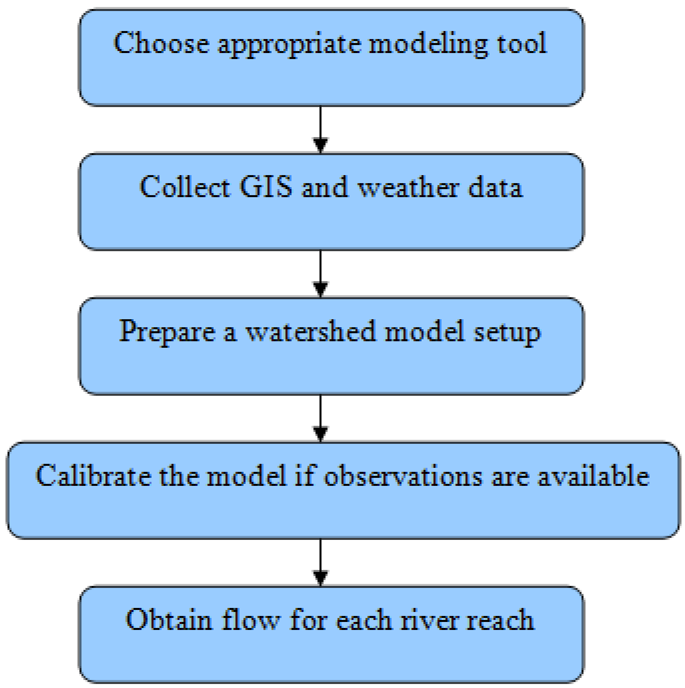

Figure 4.2: Protocol for Obtaining Stream Flow Data from Simulation Models

Using StreamStats

StreamStats (Ries, Guthrie et al. 2008) (http://streamstats.usgs.gov) is a web-based Geographic Information System (GIS) application created by USGS and Environmental Systems Research Institute Inc. (ESRI). StreamStats estimates stream flow data using regional regression equations or flow records from nearby gauging stations. It provides access to an array of analytical tools useful for water management applications, including stream flow estimation. The functionality is based on the Arc Hydro Data model and tools that are found at:
http://support.esri.com/index.cfm?fa=downloads.dataModels.filteredGateway&dmid=15.

StreamStats can be accessed through a map-based user interface using a web browser, or individual functions can be requested through other web services. StreamStats allows users to estimate flow statistics, and basin characteristics for both gauged (managed by USGS) and un-gauged sites. StreamStats also estimates flow for both fully functional semi-functional sites where only partial data are available. The web-interface automatically integrates information for stream reaches upstream and downstream of user-selected sites and locations along the stream to account for site-specific stream attributes influencing stream hydrology such as impoundments or abstractions. Information using StreamStats to obtain stream flow data is available in Appendix A2.

StreamStats was designed as a separate application for each US state relying on local partnership for funding and data collection. By June 2010, 17 states had fully functional applications, six states are in testing phase and the other states are in various stages of implementation (Figure 4.3).

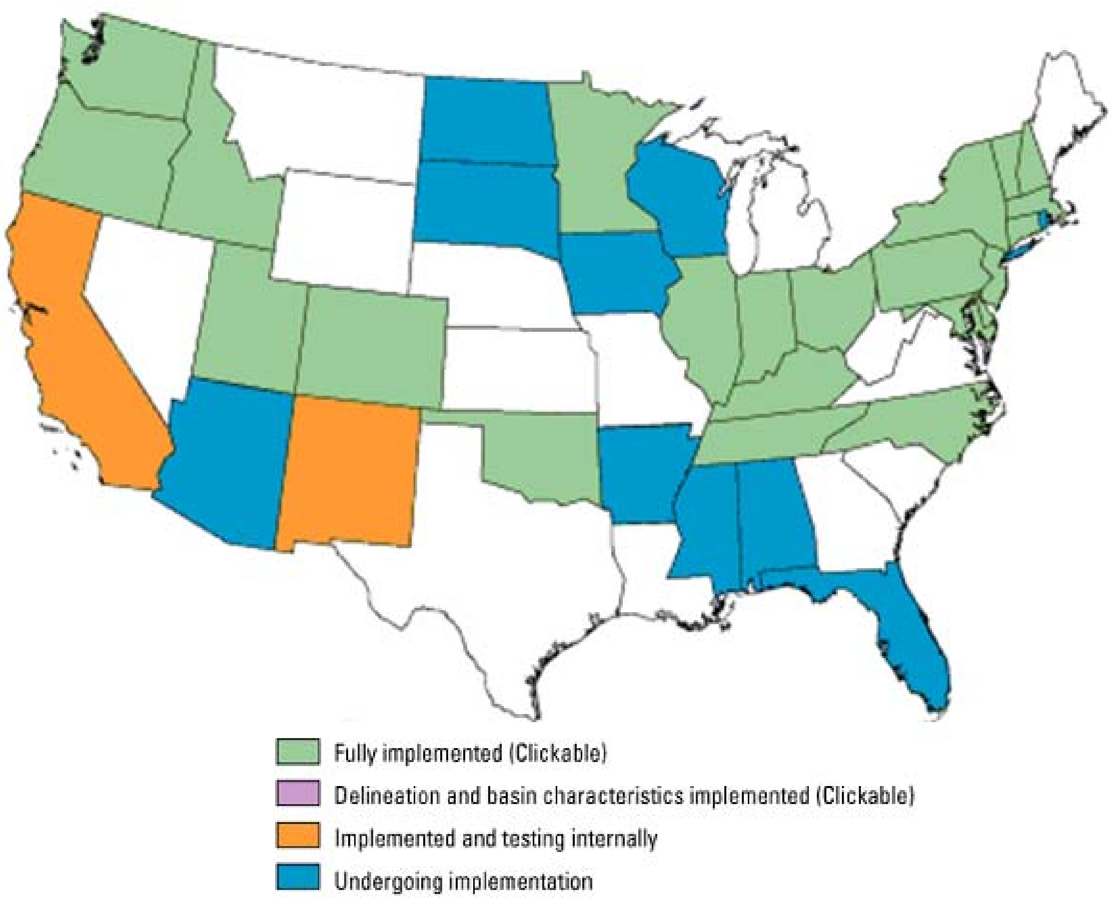

Figure 4.3: Current Status of StreamStats Implementation (Nov. 2010)

For EPA Region 6 StreamStats is fully functional in Oklahoma, being tested in New Mexico and undergoing implementation in Arkansas. Where fully available, StreamStats could be very useful tool for water management.

StreamStats functionalities include the following:

- View features such as roads, streams, political boundaries, USGS topographic maps
- Change the magnification or scale of map
- Extract information from various map layers
- Get stream flow statistics, basin characteristics, data collection stations
- Identify drainage basin boundary for selected site
- Measure basin characteristics
- Search connected upstream and downstream reaches
- Download basin boundary, basin characteristics and stream statistics
- Locate man made features such as dams, wastewater discharges

Descriptive Information on Data-Collection Stations

The descriptive information available in StreamStats includes USGS station identification number, station name, station type, period of record, latitude, longitude, hydrologic unit code (HUC), major drainage basin name, county, U.S. Census Bureau Minor Civil Division (MCD) name, directions to locate the station, and existence of any manmade features or other relevant information about the stations (Ries, Guthrie et al. 2008). Details on how to use StreamStats to obtain flow data are available in Appendix A2.

Stream Flow Statistics for Un-gauged Sites

One of the advantages of StreamStats is that it can estimate stream flow statistics for un-gauged sites on the basis of regional regression equations or flow records at or nearby gauging stations. If the drainage area of the un-gauged site is within 0.5 to 1.5 times the drainage area of stream gauging sites, flow data from upstream and downstream gauging stations may be used after being weighted by the ratio of drainage areas to estimate flow at the un-gauged site. In other cases where the ratio of drainage areas is too big or too small, regression equations may be used to estimate flow values for un-gauged sites. These equations are developed by statistically relating flow characteristics to basin characteristics such as drainage area, elevation and precipitation. Regression equations for a group of gauge stations within a region were developed (Ries, Guthrie et al. 2008). Such regression equations are available for the entire nation. Therefore, measuring basin characteristics and incorporating them into appropriate regression equations can obtain stream flow estimates for an un-gauged site. It should be noted that the data for an un-gauged site involves interpolations and extrapolations. As such, this method increases the standard error resulting in greater uncertainties associated with these data. Details on how to use StreamStats to obtain flow data are available in Appendix A2.

Using Computer Models to Estimate Stream Flow

Flow data may not be available for a river or watershed. If monitored for a river, it may not be done for all the reaches of the river. Under these circumstances, simulation models could be used to obtain flow data. A variety of hydrologic models are available. They can be empirical (using some simple equations (e.g. regression equations)), conceptual (conceptual representation of physical processes (e.g. HSPF model)) or can have a detailed representation of physical processes (MIKE SHE model). With the advances in hydrologic science and computing, models that describe the physical processes in detail are becoming popular. They come with a user interface for easy generation and manipulation of input and output. Selecting the most appropriate model is the first step to obtain flow data using a simulation model. The user has freedom to choose any model suitable for the needs of study. However, some important criteria to be considered while selecting a model are shown in Table 4.1 for the four most popular models.

The appropriate model can be chosen depending on the scale of application, data demands and computing requirements. A typical model with a detailed representation of physical processes requires elevation, soil, land cover, weather (precipitation and temperature at least) and information on land management. Elevation and land cover data can be obtained from USGS. Soil map can be obtained from National Resource Conservation Society (NRCS). Weather data is an important component of data requirements of a model. Weather data could be obtained from an array of sources:

- National Climate Data Center (NCDC: http://www.ncdc.noaa.gov/oa/ncdc.html),
- National Oceanic and Atmospheric Administration (NOAA: http://www.noaa.gov/), and the
- State Climatologist Office–Texas (http://www.met.tamu.edu/osc/).

Table 4.1: Model Selection Criteria

Characteristics	SWMM	SWAT	HSPF	AnnAGNPS
Spatial scale of application	Watershed	Watershed, river basin	Watershed, river basin	Watershed
Modeling time step	Daily, sub-daily	Daily, sub-daily	Daily, sub-daily	Daily
User interface	Available	Available	Available	Available
User support	Available	Available	Available	Available
Land management operations	Not simulated	Simulated	Not simulated	Simulated
Urbanization	Simulated	Simulated	Simulated	Simulated
Man made features	Modeled	Modeled	Modeled	Modeled
Scenario trials	Not easy	Easy	Not easy	Easy
Flow duration analysis	Not possible	Not possible	Not possible	Not possible
Source code availability	Available	Available	Available	Available
Continued development	yes	yes	yes	yes

SWMM : Storm Water Management Model

SWAT : Soil and Water Assessment Tool

HSPF : Hydrologic Simulation Program Fortran

AnnAGNPS : Annualized AGricultural Non-Point Source model

Model calibration is possible only if flow observations are available for the assessment area. A calibration improves the reliability of model estimates. Irrespective of model calibration, it is possible to obtain simulated flow values for all the river reaches (Figure 4.2). A case study is presented in Appendix C that describes how to use SWAT to obtain stream flow data.

Chapter 5: Step 3 - Identify “Hydrologic Alterations” and Divide Flow Data

“Hydrologic alteration” refers to a noticeable and significant change in stream flow attributes including magnitude, timing, frequency, duration, and rate of change of flow. It can be identified by plotting cumulative runoff against cumulative rainfall over time for the stream segment of interest. Any significant anthropogenic watershed disturbances, such as land cover change, can alter the relationship between rainfall and runoff. The procedure used to identify “hydrologic alteration(s)” in a flow data set is illustrated below using data from the White Rock Creek watershed. Identifying “hydrologic alteration” involves the following steps:

1. Collect stream flow data,
2. Collect precipitation data corresponding to flow data,
3. Compute cumulative values for stream flow and precipitation data (Figure 5.1),
4. Plot cumulative flow (dependent variable) on the X-axis against cumulative precipitation (independent variable) on the Y-axis (Figure 5.2),
5. Identify flow trends and draw slope lines onto graph (Figure 5.3, Figure 5.4), and
6. Use the intersection of the slope lines to identify hydrologic change (Figure 5.5).

After collecting data, computation of cumulative values for flow and precipitation data is carried out (Figure 5.1). For plotting, cumulative precipitation (independent variable) must appear on the X-axis and cumulative flow (dependent variable) is shown on the Y-axis (Figure 5.2).

	A	B	C	D	E	F
1	DATE	PRECIP_MM	FLOW_MM	CUM_PRECIP	CUM_FLOW	
2	1/1/1962	0.00	0.257	0.00	0.257	
3	1/2/1962	0.00	0.257	0.00	0.514	
4	1/3/1962	1.63	0.257	1.63	0.771	
5	1/4/1962	5.56	0.471	7.19	1.242	
6	1/5/1962	0.00	0.300	7.19	1.542	
7	1/6/1962	0.00	0.257	7.19	1.799	
8	1/7/1962	0.00	0.257	7.19	2.056	
9	1/8/1962	0.00	0.257	7.19	2.313	
10	1/9/1962	3.18	0.257	10.36	2.570	
11	1/10/1962	1.66	0.286	12.02	2.856	
12	1/11/1962	0.00	0.271	12.02	3.127	
13	1/12/1962	0.00	0.271	12.02	3.399	
14	1/13/1962	0.00	0.300	12.02	3.699	
15	1/14/1962	5.92	0.428	17.94	4.127	
16	1/15/1962	1.02	0.343	18.96	4.470	
17	1/16/1962	0.00	0.286	18.96	4.755	
18	1/17/1962	0.00	0.257	18.96	5.012	
19	1/18/1962	0.09	0.257	19.04	5.269	
20	1/19/1962	0.22	0.257	19.26	5.526	
21	1/20/1962	0.00	0.228	19.26	5.755	
22	1/21/1962	0.87	0.243	20.12	5.998	
23	1/22/1962	3.96	0.300	24.08	6.297	
24	1/23/1962	1.49	0.257	25.56	6.555	
25	1/24/1962	0.00	0.300	25.56	6.854	
26	1/25/1962	0.51	0.328	26.07	7.183	
27	1/26/1962	3.60	0.457	29.67	7.640	
28	1/27/1962	0.00	0.300	29.67	7.940	
29	1/28/1962	0.00	0.271	29.67	8.211	
30	1/29/1962	0.00	0.257	29.67	8.468	
31	1/30/1962	0.00	0.257	29.67	8.725	

Figure 5.1: Computing Cumulative Values of Precipitation and Flow

"Hydrologic alterations" are revealed with visible trends in the graphs below (Figure 5.2 to Figure 5.5). Figure 5.3 and Figure 5.4 clearly identify different trends in stream flow data. This deviation from the straight-line slope for the values of cumulative flow vs. cumulative precipitation marks a change in stream flow. The unit of time corresponding to the intersection of the slope lines is the point in time when a significant hydrologic change has occurred. In the case of the White Rock Creek watershed, a notable hydrologic alteration occurred in 1980 (Figure 5.5). Thus, to estimate the current stream health, the flow data are then divided into two groups or parts. One set of stream flow data represents the pre-alteration period from 1962-1980 while the other set represents the post-alteration period from 1981-2007. Hydrologic indices will be estimated separately for these two periods and then analyzed to identify changes in stream health.

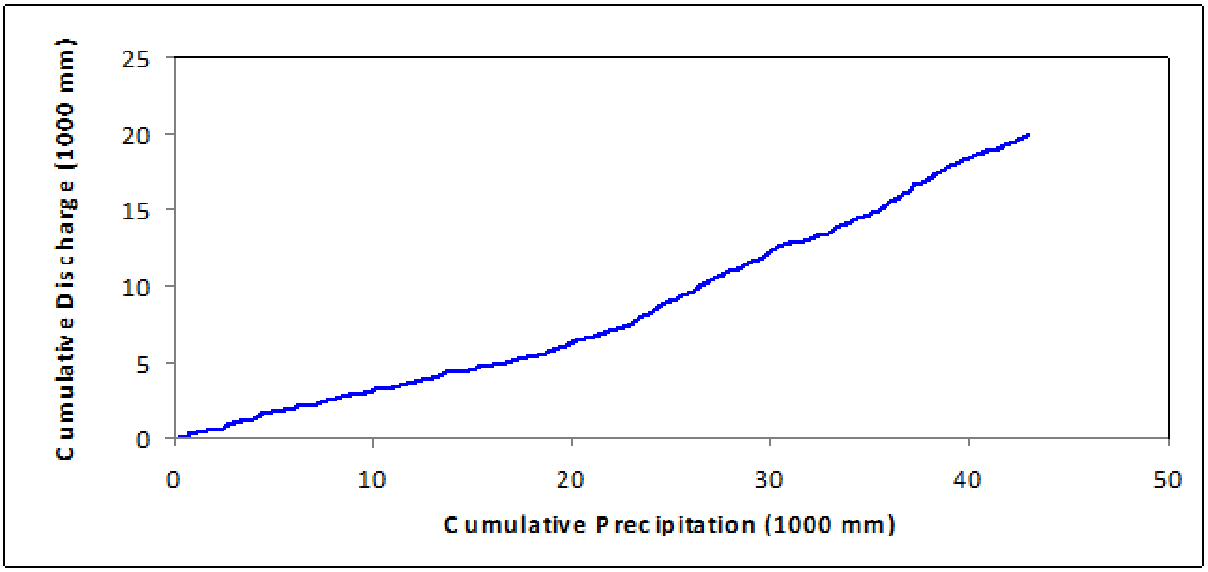

Figure 5.2: Cumulative Precipitation vs. Cumulative Discharge – White Rock Creek Watershed

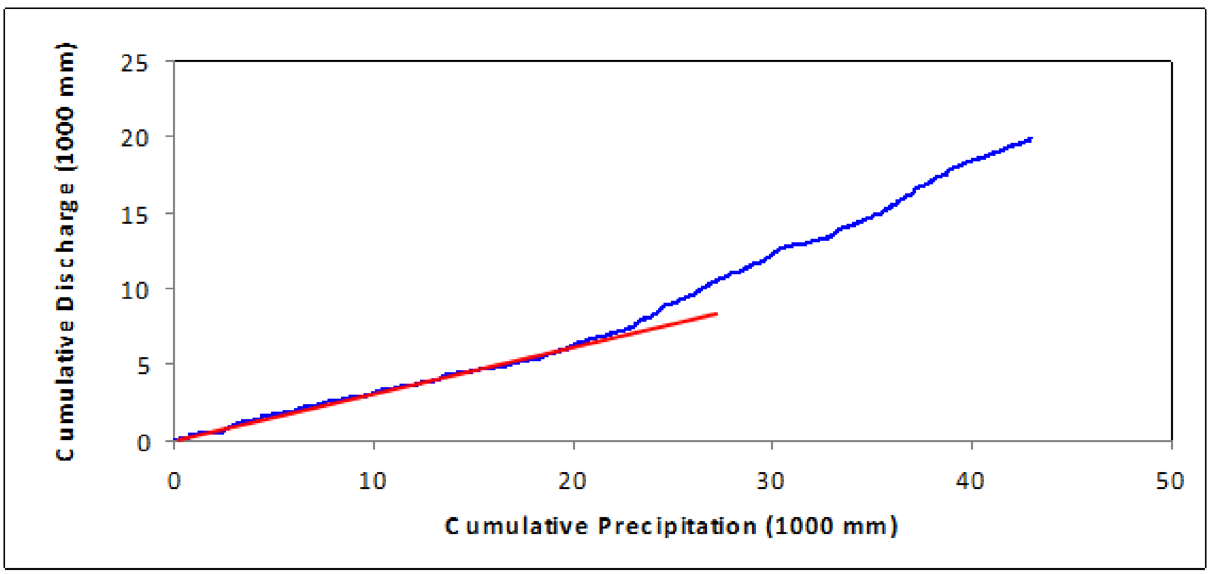

Figure 5.3: Identification Trends in Flow Data – White Rock Creek Watershed

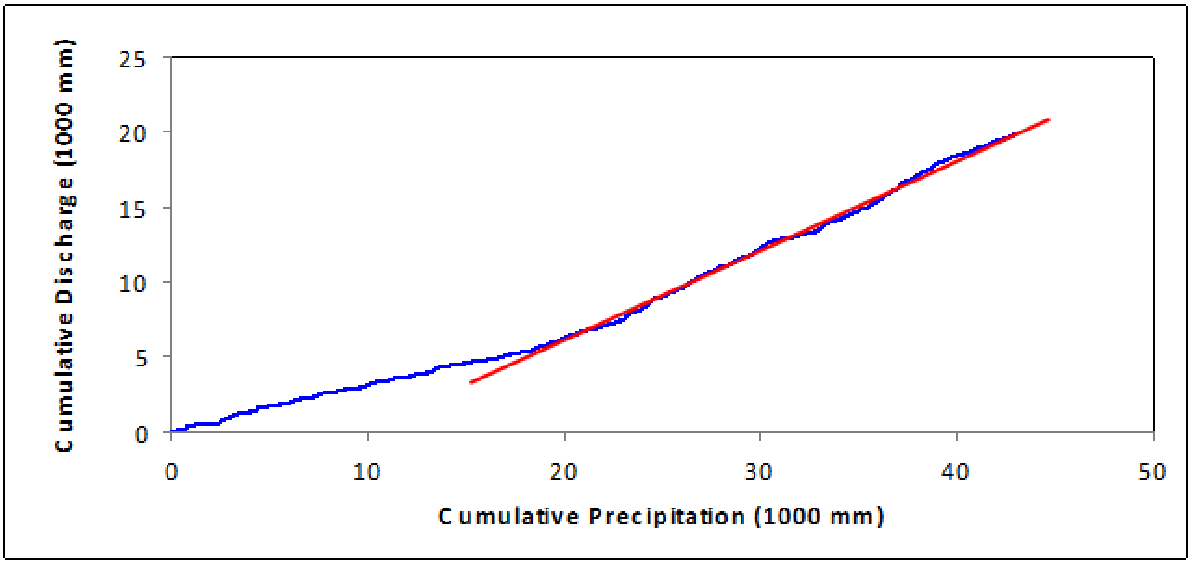

Figure 5.4: Identification of Trends in Flow Data – White Rock Creek Watershed

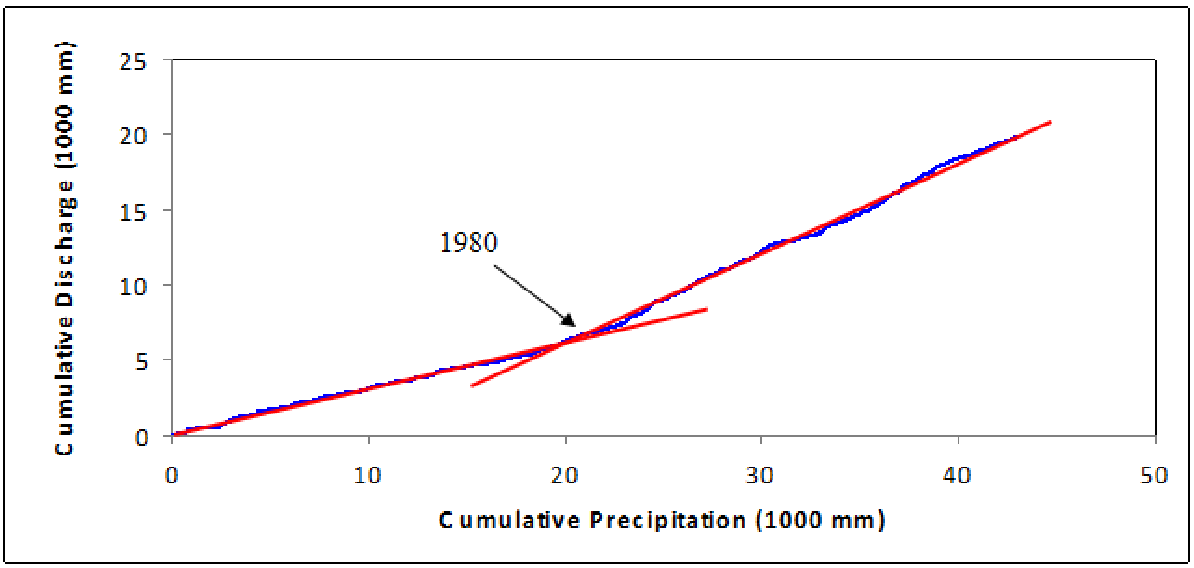

Figure 5.5: Identification of Hydrologic Alteration – White Rock Creek Watershed

Chapter 6: Step 4 – Use Appropriate Tools to Generate Flow Duration Curves and Indices of Hydrologic Alternation

Software tools are available to generate flow duration curves (FDCs) and indices of hydrologic alteration. This section discusses two widely used tools: NATional Hydrologic Assessment Tool (NATHAT) developed by the USGS and Indices of Hydrologic Alteration (IHA) developed by The Nature Conservancy.

NATional Hydrologic Assessment Tool (NATHAT)

To assess hydrologic alterations in stream flow and to establish environmental flow standards, USGS scientists have developed the NATional Hydrologic Assessment Tool (NATHAT). NATHAT is intended for use by those interested in managing or regulating streams to restore or maintain ecological integrity. To date, a customized version of the tool has been completed for New Jersey only, but versions are under development for many other states.

NATHAT can estimate many hydrologic indices to characterize the magnitude, frequency, duration, timing, and rate of change of stream flow. It computes 171 hydro-ecological indices (Appendix A3) for specified periods of record. The tool requires daily stream flow data in a specific format (outlined in the next chapter) for computation of hydro-ecological indices. If daily peak stream flow data are also included, then eight additional indices can be calculated. USGS flow data can be directly imported into NATHAT for analyzing flow data.

NATHAT requires an output file name to write the indices computed. The other parameters required to run the analysis are the drainage area, lower and upper limits for the index as percentiles (confidence limits). The user has to enter the drainage area and confidence limits. Most users select the confidence limits of 25% and 75%. However, any other limits can also be used. The indices computed by the tool can be broadly categorized into magnitude, frequency, duration, timing and rate of change. The indices are named with special codes to reflect the category to which they belong. Magnitude, frequency, duration, timing and rate of change are coded as parameters starting with M, F, D, T and R respectively. The sub-categories of flow such as low flow, high flow and average are coded as L, H and A respectively. Usually the sub-category codes will appear as the second letter in the parameter code, e.g. MA is magnitude of an average flow event. The NATHAT program is freely available from the USGS website available at http://www.fort.usgs.gov/Products/Software/NATHAT/. The software comes with a help menu, file format requirements and the definition of indices computed by the program.

The National Hydrologic Assessment Tool (NATHAT) is based on a hydrologic classification of streams (Poff 1996) involving 420 gauging stations across the United States. Using NATHAT, with daily average and peak stream flow data we can:

- Establish a hydrologic baseline (reference time period),
- Establish environmental flow standards, and
- Evaluate past and proposed hydrologic modifications.

Six stream classes are available in NATHAT. However, NATHAT does not have the capability to identify the stream type. Therefore, the user must input the stream type that is being examined by the tool. More details on stream classification are discussed in Chapter 8 and can also be obtained direct from publications (Poff 1996; Olden and Poff 2003). Apart from the computation of hydro-ecological indices, NATHAT has the capability to graph flow as per user specifications and generate flow statistics. It can graphically represent the generated hydrologic indices (Appendix A3). A summary of the capabilities of NATHAT is shown in (Table 6.1). Hydrologic Index Tool (HIT) is another tool developed by USGS that has many capabilities of NATHAT as a sub-package. It is used to generate indices of hydrologic operation for multiple USGS gauge records in batch processing mode. This is the advantage of using HIT over NATHAT.

Table 6.1: Features Comparison of NATHAT and IHA

Capability	NATHAT	IHA
User friendly interface	Available	Available
Direct use of downloaded USGS flow data	Possible	Possible
Generation of flow duration curves (FDCs)	Possible	Possible
Generation of FDCs for any user-defined statistic	Available	Some limitations
Generation of indices of hydrologic operation	Available	Available
Total number of flow/ecology related indices	171	67
Confidence limits for indices	Available	Available
Flexibility to change confidence limits of indices	Available	Available
Provision to graph flow data	Available	Some limitations
Provision to export the generated graphs and tables	Available	Available

Indicator of Hydrologic Alteration (IHA)

Indicator of Hydrologic Alteration (IHA) is a software tool developed by The Nature Conservancy for calculating the characteristics of natural and altered hydrologic regimes (The Nature Conservancy 2007). The IHA software is available at:

http://conserveonline.org/workspaces/iha.

The program runs under any version of the Microsoft Windows operating system. The IHA requires daily hydrologic data for the calculation of its statistics. Richter et al. suggest that daily hydrologic records of 20 years is necessary to guarantee meaningful results for pre- and post-impacted time periods using the IHA method. Daily stream flow data downloaded from the U.S. Geological Survey (USGS) website http://water.usgs.gov/usa/nwis can be imported directly into IHA. Simulated daily average flow in cubic feet per second or cubic meters per second can also be loaded into the program for analyses.

The IHA method calculates a total of 67 statistical parameters including 33 IHA parameters and 34 Environmental Flow Component (EFC) parameters. A hydrologic data set can be divided into two distinct time periods if the hydrologic system experienced an abrupt change such as a dam construction or rapid urbanization. In general, non-parametric statistics (percentiles) are recommended over parametric statistics (mean/standard deviation) because of the skewed nature of hydrologic data sets. IHA output is displayed on-screen in formatted graphs and can be exported to use with spreadsheet software such as Microsoft Excel. The output spreadsheet includes: (1) annual summary statistics, (2) IHA statistics summary scorecard, (3) linear regression, for identifying trends in the data, (4) IHA percentile data, (5) daily EFC flow characterization, (6) flow duration curve data analysis, and (7) messages and warnings regarding the results generated.

The 32 IHA parameters are categorized in five groups (Table 6.2) and the different characteristics of each IHA group implies different ecological influences to streams or lakes. The IHA calculates 34 EFC parameters in five different types: low flow, extreme low flows, high flow pulses, small floods, and large floods. These five types of flow events cover the full spectrum of flow conditions that must be maintained to sustain riverine integrity. By default, the threshold values for each type is >75% for high flows, <50% for low flows, <10% for extreme low flow, two-year return flow for small floods, and ten-year return flow for large floods (Swanson 2002; The Nature Conservancy 2007).

Table 6.2: List of 32 IHA parameters (Black, Rowan et al. 2005)

Group 1. Magnitude of monthly water conditions
Example of ecological relevance: habitat availability for aquatic organisms
Mean January flow
Mean February flow
Mean March flow
Mean April flow
Mean May flow
Mean June flow
Mean July flow
Mean August flow
Mean September flow
Mean October flow
Mean November flow
Mean December flow
Group 2. Magnitude and duration of annual extremes
Example of ecological relevance: structuring of river channel morphology and physical

habitat conditions

- 1-day-minimum flow
- 1-day-maximum flow
- 3-day-minimum flow
- 3-day-maximum flow
- 7-day-minimum flow
- 7-day-maximum flow
- 30-day-minimum flow
- 30-day-maximum flow
- 90-day-minimum flow
- 90-day-maximum flow

Group 3. Timing of annual extremes

Example of ecological relevance: compatibility with life cycles of organisms

- Date of 1-day maximum flow
- Date of 1-day-minimum flow

Group 4. Frequency and duration of high and low pulses

Example of ecological relevance: frequency and duration of anaerobic stress for plants

- Annual number of high pulses
- Annual number of low pulses
- Mean duration of high pulses (days)
- Mean duration of low pulses (days)

Group 5. Rate and frequency of change in conditions

Example of ecological relevance: entrapment on islands and floodplains

- Mean daily flow increase
- Mean daily flow decrease
- Number of rises
- Number of falls

Chapter 7: Step 5 – Create Flow Duration Curves and Indices of Hydrologic Alteration

This chapter describes the step by step procedure to arrange flow data and to create flow duration curves and indices of hydrologic alteration. In addition, it describes a method to estimate changes in channel dimensions resulting from hydrologic alterations.

Flow Duration Curves

A flow duration curve (Figure 7.1) illustrates the percentage of time, or probability, that flow in a stream will equal or exceed a particular value. Flow duration curve analysis is a method involving the frequency of historical flow data over a specified period. Typically, low flows (flow during prolonged dry spells) are exceeded a majority of the time, while high flows, such as those resulting in floods, are exceeded infrequently.

A basic flow duration curve measures high flows to low flows along the X-axis (Figure 7.1). The X-axis represents the percentage of time (known as duration or frequency of occurrence) that a particular flow value is equaled or exceeded. The Y-axis represents the quantity of flow at a given time step, e.g., cubic feet per second (cfs), associated with the duration. Flow duration intervals are expressed as percentage of exceedance, with zero corresponding to the highest stream discharge in the record (i.e., flood conditions) and 100 to the lowest (i.e., drought conditions). For instance, a flow duration interval of 35% associated with a stream discharge of 11 cfs implies that 35% of all observed daily average stream discharge values equal or exceed 11 cfs.

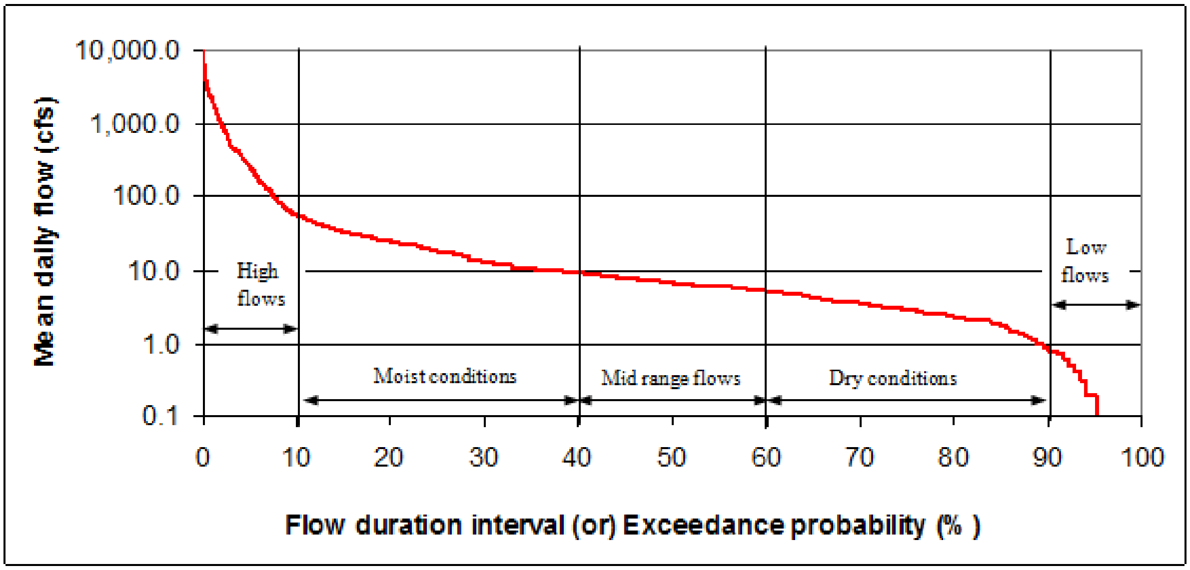

Figure 7.1: Flow Duration Curve

Create Flow Duration Curves

Flow data are used to generate a flow duration curve. Creating a flow duration curve involves four basic steps.

- Acquire stream flow data (as discussed in Chapter 4),
- Arrange data (in descending order),
- Rank flow data (Figure 7.2), and
- Obtain frequency of occurrence (or exceedance probabilities).

Frequency of occurrence is obtained using the following formula:

$$F = 100 * \frac{R}{N+1}$$

Where,

F is frequency of occurrence (expressed as % of time a particular flow value is equaled or exceeded)

R is Rank

N is Number of observations

As an example, frequency of occurrence or exceedance probability for flow value 9.176 is calculated as follows:

$$F = 100 \times \frac{6}{38+1}$$

$$F = 15.38$$

Plot the sorted flow rate (Y-axis) against the exceedance probability (X-axis) to generate flow duration curve.

A	B	C
Flow (cfs)	Rank	Exceedance probability (%)
48.098	1	2.56
26.482	2	5.13
17.464	3	7.69
13.857	4	10.26
11.037	5	12.82
9.176	6	15.38
7.658	7	17.95
6.642	8	20.51
6.341	9	23.08
5.654	10	25.64
2.305	11	28.21
1.575	12	30.77
1.231	13	33.33
1.016	14	35.90
0.845	15	38.46
0.730	16	41.03
0.644	17	43.59
0.558	18	46.15
0.501	19	48.72
0.458	20	51.28
0.415	21	53.85
0.372	22	56.41
0.329	23	58.97
0.301	24	61.54
0.243	25	64.10
0.186	26	66.67
0.132	27	69.23
0.084	28	71.79
0.080	29	74.36
0.073	30	76.92
0.066	31	79.49
0.057	32	82.05
0.047	33	84.62
0.043	34	87.18
0.039	35	89.74
0.034	36	92.31
0.030	37	94.87
0.019	38	97.44

Figure 7.2: Flow Data for Creating a Flow Duration Curve

Not all streams or water bodies have gauging stations or flow data available. In such cases estimation techniques are needed (USEPA 2007). For instance, it may be appropriate to use flow data from a similar, but representative water body to develop a flow duration curve based on regression methods or drainage area ratios. Rainfall-runoff models such as SWAT can also be used to develop stream flow estimates for use in a duration curve analysis (Chapter 4).

Flow Duration Curve Intervals and Zones

Flow duration curve analysis identifies intervals, which can be used as a general indicator of hydrologic conditions (i.e., wet versus dry and severity). Flow duration curve intervals can be grouped into several broad categories, or zones. These zones provide additional insight about conditions and patterns associated with the impairment. A common way to look at the duration curve is by dividing it into five zones, as illustrated in (Figure 7.1), representing ***high flows*** (0-10%), ***moist conditions*** (10-40%), ***mid-range flows*** (40-60%), ***dry conditions*** (60-90%), and ***low flows*** (90-100%).

This approach places the midpoints of the moist, mid-range, and dry zones at the quartiles (25^{th}, 50^{th}, and 75^{th} percentiles, respectively). The high zone is centered at the 5^{th} percentile, while the low zone is centered at the 95^{th} percentile. Ranges can be adjusted, depending on local hydrology and the relevant water quality issues being addressed. Although five zones are commonly used to derive additional information from FDCs, the number of zones and range of frequency values are decided based on local hydrologic conditions.

Indices of Hydrologic Alteration

Indices of hydrologic alteration can be obtained by following the four basic steps given below:

- Obtain flow data, as discussed in Chapter 4.
- Arrange flow data into pre-alteration and post-alteration data sets after identifying hydrologic alteration. Details on this process can be found in Chapter 5.
- Select a tool to generate hydrologic indices. For overall estimation of stream health, IHA is recommended, while NATHAT should be used when a more detailed analysis of stream health is needed (e.g. impacts on riparian vegetation, impacts on macro invertebrates). A detailed discussion on this is provided in Chapter 6.
- Format flow data. IHA and NATHAT tools used to generate hydrologic indices can read USGS flow data files directly. In addition, both tools can use flow data in specific format (flow data format for NATHAT is given here):

Year	Year1,	Year2,	Year3,	...,......,..	Last Year
flow_day1	day1_flow,	day1_flow,	day1_flow,	...,......,..	day1_flow
flow_day2	day2_flow,	day2_flow,	day2_flow,	...,......,..	day2_flow
.					
.					
flow_day366	day366_flow,	day366_flow,	day366_flow,	...,......,..	day366_flow
num_peaks	Number of peak flow values (n)				
peak flows	peak flow 1,	peak flow 2,	peak flow 3,	...,......,..	peak flow n
Mean flow for	peak flow day1,	peak flow day2,	peak flow day 3,	...,......,..	peak flow n

Note:

a) Column 1 is shown for illustration purpose only. They are not a part of the input file

b) Year should be defined in YYYY format

c) If Day 366 is not available in a year it can be left blank

d) Number of years of peak flow should normally correspond to number years of flow data availability. If any of the data is not available they need to be left blank.

e) Flow values can be arranged in a comma-separated format (.csv format) using spreadsheet (Microsoft-Excel) program or any other text editor

An example data set is given below:

Year	1932,	1933,	1934,	1935,	1936,	1937,	1938,	1939,	1940
flow_day1	5.6,	7.5,	5.8,	11,	27,	28,	23,	6.3,	4.8
flow_day2	5.6,	7.5,	3.8,	9.7,	23,	27,	17,	6.3,	4.6
,	7.8,	,	,	,	32,	,	,	,	33
9									
peak_flow	3980,	3370,	2880,	4060,	78500,	4820,	12000,	707,	11000
average_flow	3820,	2510,	2080,	3550,	43800,	2360,	6200,	234,	4920
Year	1932,	1933,	1934,	1935,	1936,	1937,	1938,	1939,	1940

Note: The gap after comma is provided for illustration purpose only. They are not needed. Only leap years have flow value on day 366 (years 1932, 1936 and 1940 in this case).

After arranging flow data, the following steps need to be followed to generate hydrologic indices with NATHAT (Figure 7.3 to Figure 7.6).

Generating Hydrologic Indices using the NATHAT Program

To create a new project, open the NATHAT program and select New Project under the File menu (Figure 7.3). The new project needs a name and a small description.

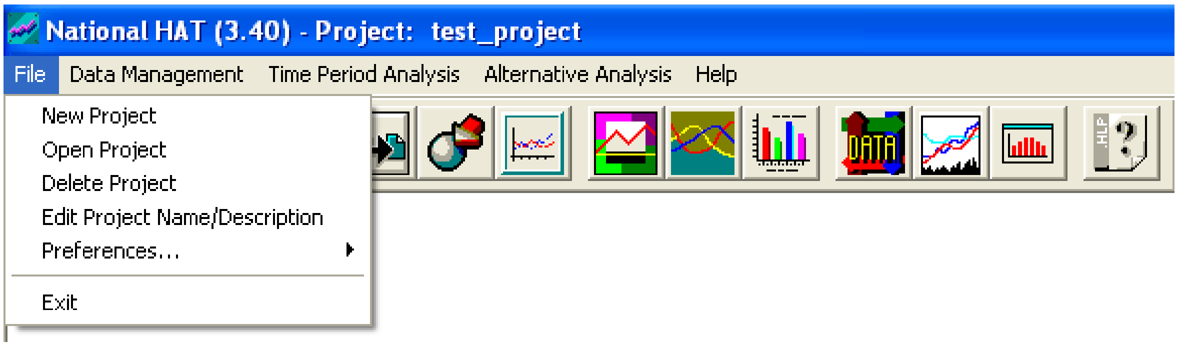

Figure 7.3: Create New Project

To import flow data (USGS format or comma separated (.csv) format) can be chosen from the Data Management menu of the NATHAT program (Figure 7.4).

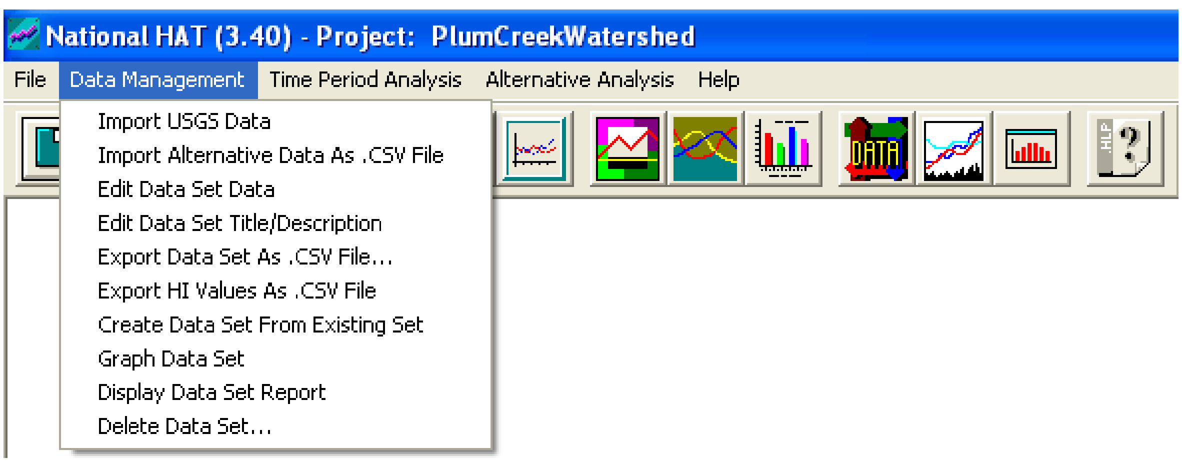

Figure 7.4: Import Flow Data

A stream type should be selected from the list of available categories. This step appears soon after importing flow data.

Create time period profile (data can be separated into pre- and post-alteration period) using the Time Period Analysis menu of NATHAT program (Figure 7.5). A maximum of five different time periods can be analyzed at the same time using NATHAT (Figure 7.6).

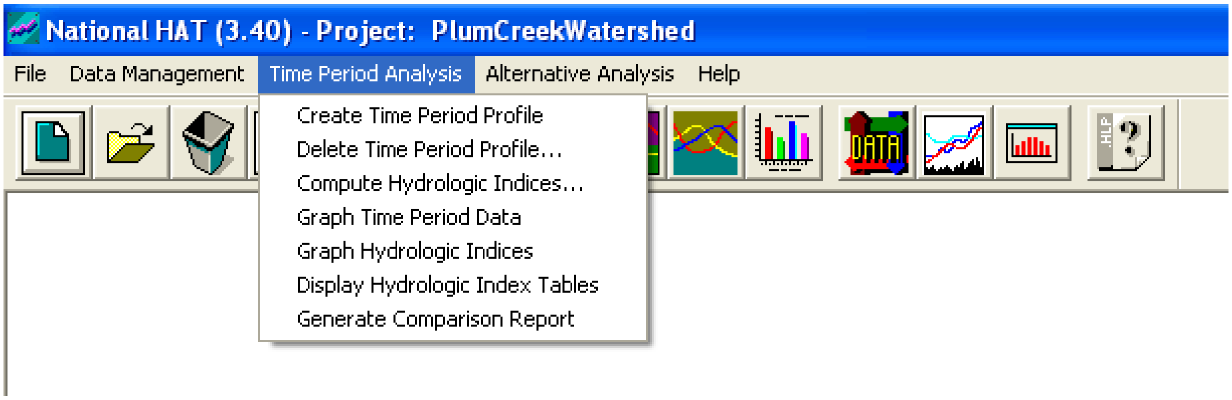

Figure 7.5: Display flow data / hydrologic indices

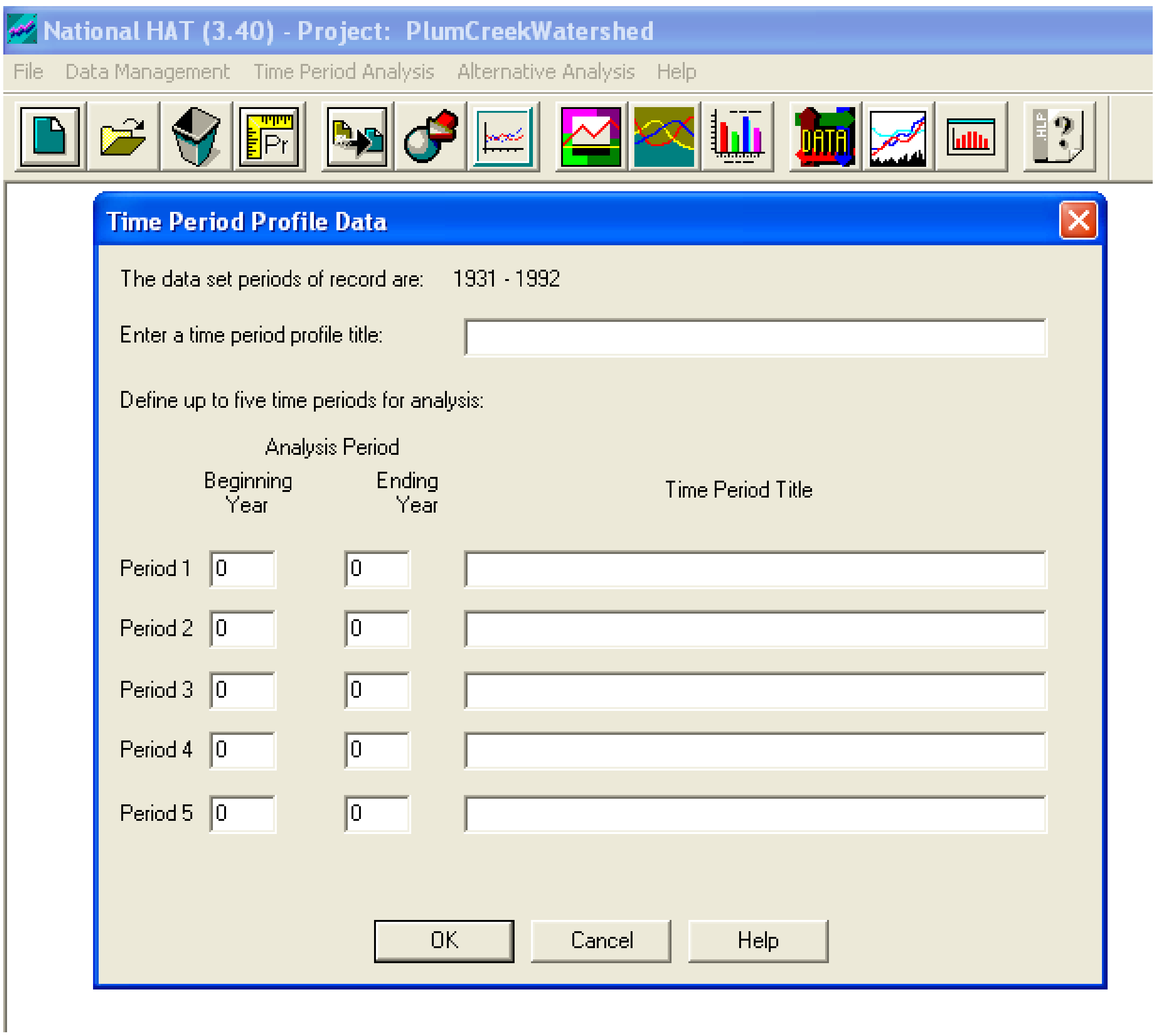

Figure 7.6: Create Time Period(s)

Compute hydrologic indices using the Time Period Analysis menu of NATHAT (Figure 7.5)

Generating Hydrologic Indices using using IHA Method

Use IHA Wizard to import hydrologic data into the IHA program which appears when the program first starts, or by selecting menu option in the IHA|Wizard (Figure 7.7).

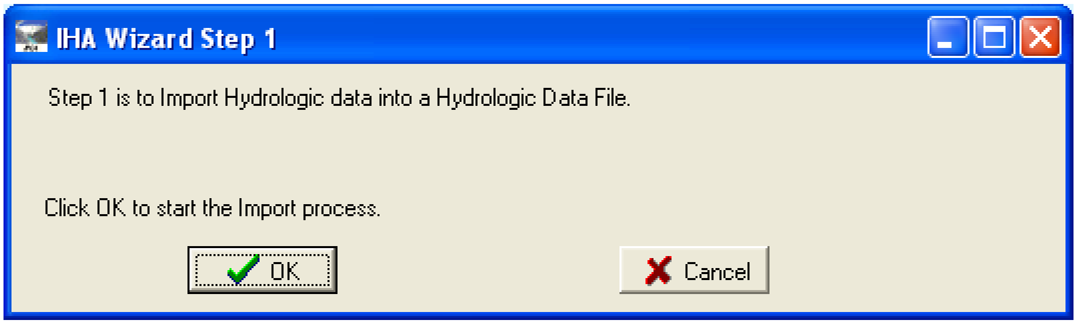

Figure 7.7: Import Hydrologic Data

Create a new project by selecting IHA|Project|Start New Project. Select one or two flow data (Hydro Data) files to use with the project. Provide detailed information such as flow rate units and the water year definition (Figure 7.8).

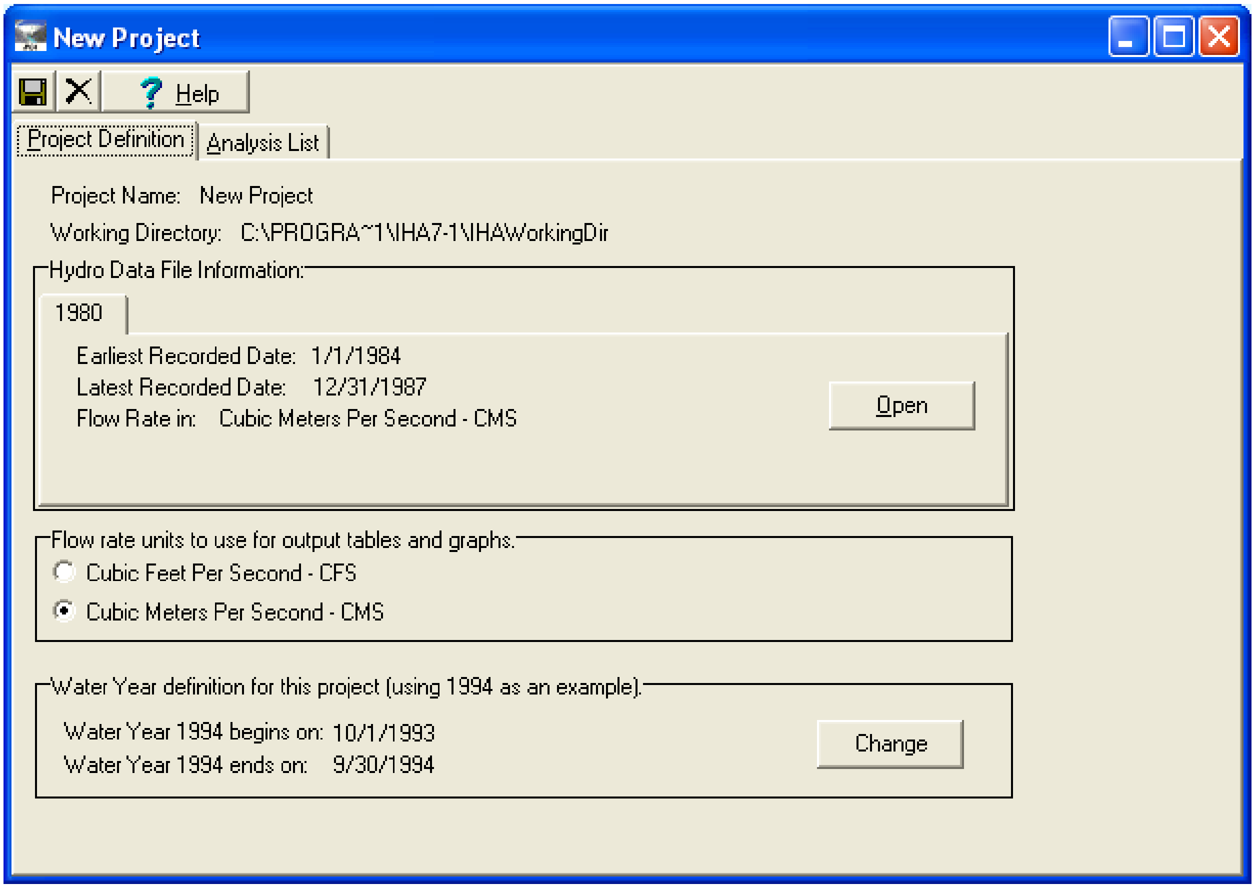

Figure 7.8: Create New Project

An IHA project is linked to one or two Hydro Data files, but can contain multiple analyses. Create an Analysis in this project using the Analysis Wizard (Figure 7.9).

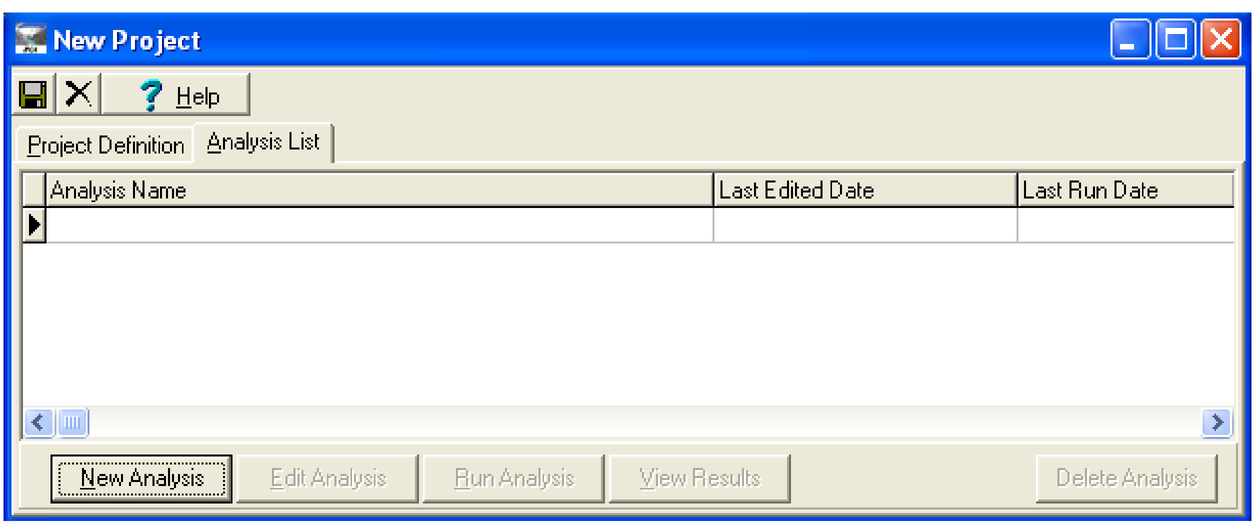

Figure 7.9: Create an Analysis for New Project

Divide the data into pre-impact and post-impact periods for a two-period analysis. The user can select a single period analysis alternatively (Figure 7.10).

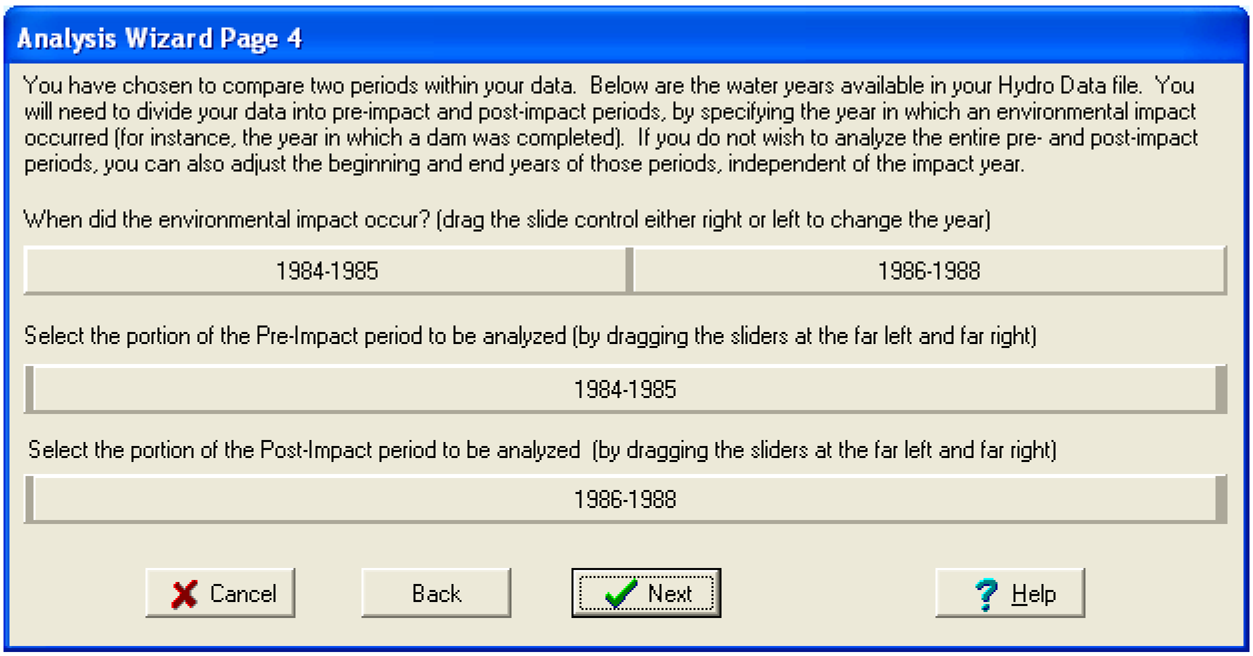

Figure 7.10: Define Data Periods

Select Parametric or Non-Parametric Statistics. IHA parameters can be calculated as parametric (mean/standard deviation) or non-parametric (percentile) statistics. A key assumption of parametric statistics is that the data are normally distributed. Non-parametric statistics are often useful because of the skewed (non-normal) nature of many hydrologic datasets (Figure 7.11).

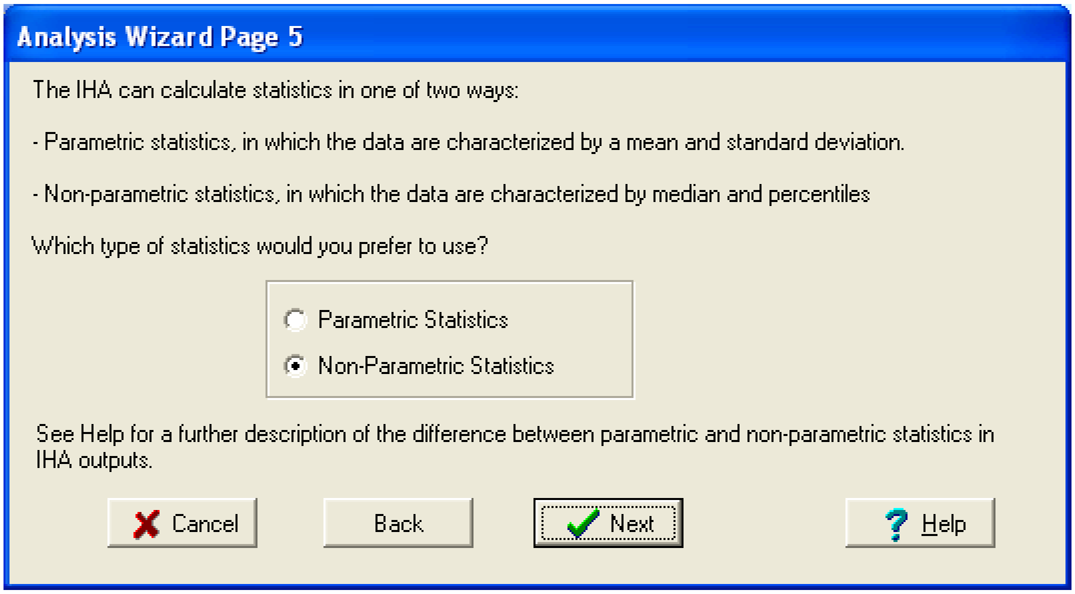

Figure 7.11: Select Usage Type for Statistics

Run the analysis. See IHA manual for more advanced features of the IHA Analysis options (Figure 7.12).

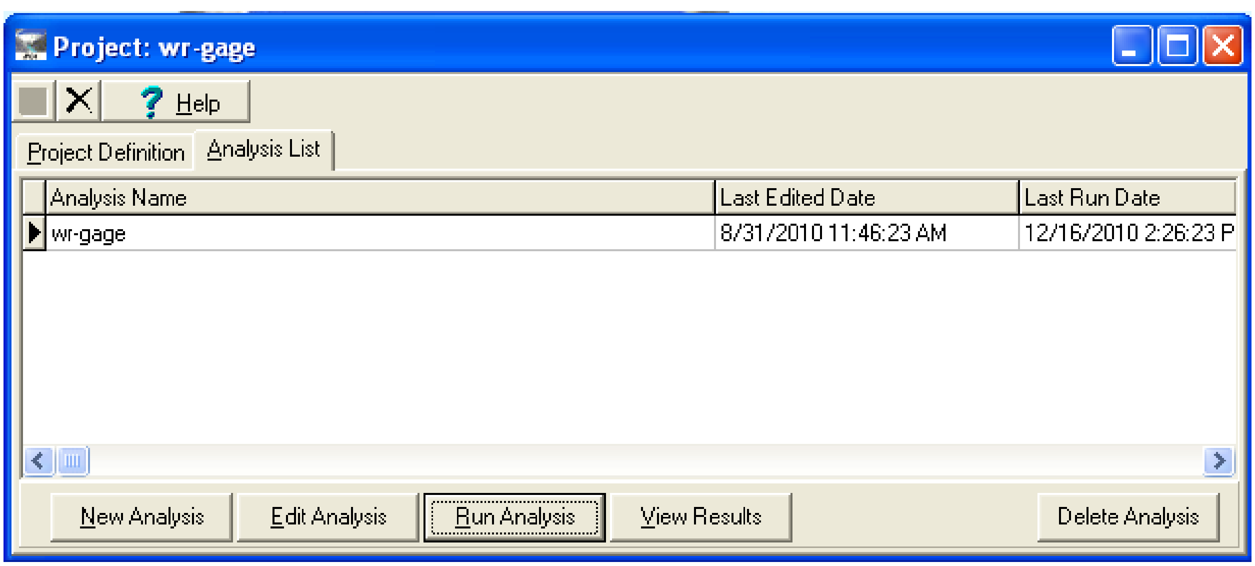

Figure 7.12: Run Analysis

Visualize IHA output in graphs by selecting View Results|View Graph, or export the calculated IHA output to spreadsheet tables by selecting View Results|View Tables (Figure 7.13).

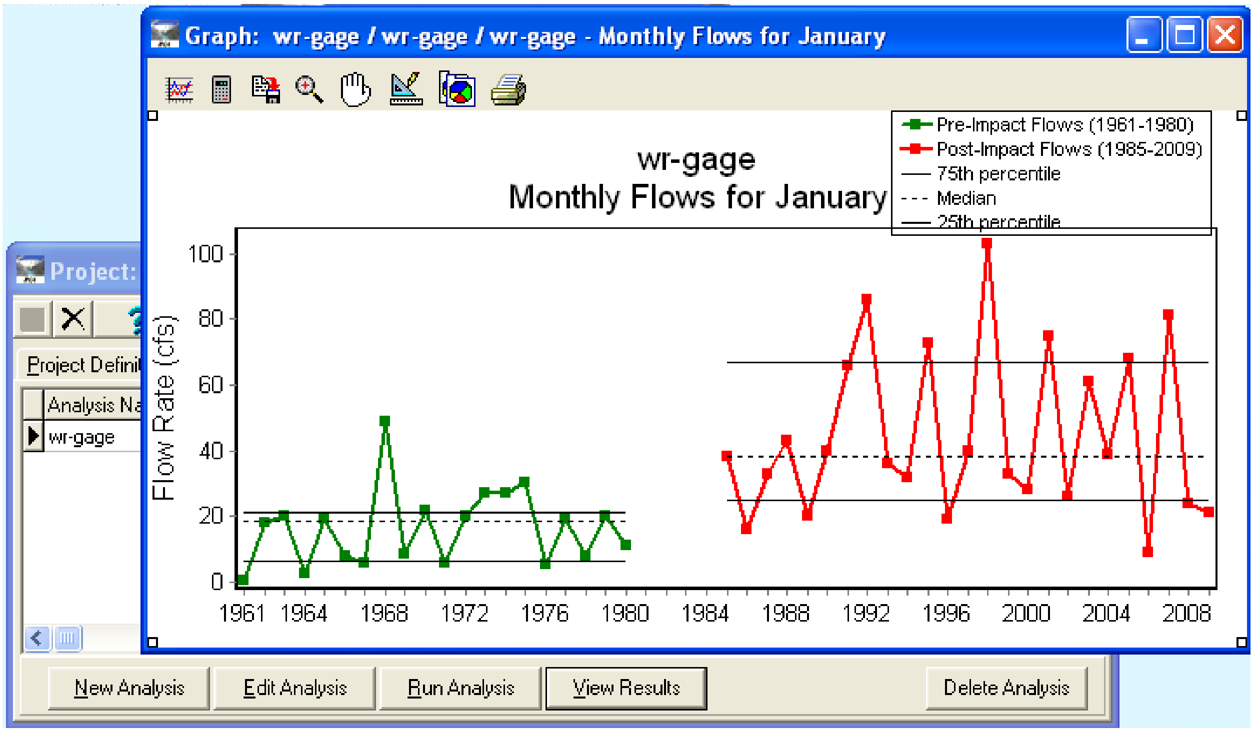

Figure 7.13: View Output

Estimating Changes in Channel Dimensions

Energy of a stream is closely associated with the flow rate. A stream with more energy is more likely to erode its channel. Stream channel dimensions are related to habitat availability for aquatic organisms and supporting riparian vegetation. Therefore, any changes to channel dimensions are expected to bring changes to aquatic organisms and riparian vegetation. Hence, assessing the changes in channel dimensions due to changes in flow pattern is important to estimate changes in stream health. This section describes a method using flow data to estimate changes in channel dimensions as a result of hydrologic alterations. The approach is based on an assumption (common for computational purposes) that the river/stream channel is trapezoidal and it is hydraulically efficient.

Area of trapezoidal channel = $A = (b + zd) \times d$ (1)

Where,

A is area of cross section of channel

b is width

d is depth and

z is bed slope

For hydraulically efficient trapezoidal cross section,

$$z = \frac{\sqrt{3}}{3} \tag{2}$$

and

$$d = \frac{\sqrt{3}}{2} b \tag{3}$$

Substituting equations (2) and (3) into equation 1, we have

Or $b = \frac{2d}{\sqrt{3}}$ (4)

Therefore Area (A) = $(\frac{2d}{\sqrt{3}} + \frac{\sqrt{3}}{3} \times d) \times d$ (5)

Or $= d^2 \times (\frac{2}{\sqrt{3}} + \frac{\sqrt{3}}{3})$ (6)

$$A = 1.732 \times d^2 \tag{7}$$

Wetted perimeter (P) = $b + 2d\sqrt{1 + z^2}$ (8)

$$P = \frac{2d}{\sqrt{3}} + 2d\sqrt{1 + (\frac{\sqrt{3}}{3})^2} \tag{9}$$

$$= \frac{2d}{\sqrt{3}} + 2d\sqrt{1 + \frac{3}{9}} \tag{10}$$

$$= 2d(\frac{1}{\sqrt{3}} + \frac{\sqrt{12}}{3}) \tag{11}$$

$$= 3.464\, d \tag{12}$$

Hydraulic radius $R = \frac{A}{P}$ (13)

$$= \frac{1.7321\, d^2}{3.464 d} \tag{14}$$

$$R = 0.5\, d \tag{15}$$

Manning's Equation

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \quad (16)$$

Where, V is flow velocity

n is Manning's roughness coefficient and

S is channel bed slope

$$= \frac{1}{n} 0.592256 \times d^{\frac{2}{3}} \times S^{\frac{1}{2}} \quad (17)$$

$$Q = A \times V \quad (18)$$

$$Q = 1.7321 \times d^2 \times \frac{1}{n} \times 0.592256 \times d^{\frac{2}{3}} \times S^{\frac{1}{2}} \quad (19)$$

$$= \frac{1.0258 \times d^{\frac{8}{3}} \times S^{\frac{1}{2}}}{n} \quad (20)$$

$$d^{\frac{8}{3}} = \frac{Q \times n}{1.0258 \times S^{\frac{1}{2}}} \quad (21)$$

$$d = \left(\frac{0.97485 \times Q \times n}{S^{\frac{1}{2}}}\right)^{\frac{3}{8}} \quad (22)$$

S and n can be estimated from standard tables (e.g. available in hydraulics books, model user manual etc.) using channel condition. Therefore, channel depth can be estimated for pre- and post-alteration scenarios by using equation 22 using flow alone. Once the depth is known, width can be estimated by using equation 4 describing width-depth relationship. For flow mean daily flow or median daily flow during pre- and post-alteration periods could be used with equation 22.

Chapter 8: Step 6 – Select Ecologically Relevant Hydrologic Indices

Two widely used tools, IHA and NATHAT, generate hydrologic indicators required for estimating stream health. They generate about 67 and 171 hydrologic indices respectively, describing various statistics of flow data. Many of those indicators are inter-correlated (Olden and Poff 2003) and therefore make the computation numerically redundant. This complicates the environmental assessments (Arthington, Bunn et al. 2006). Therefore, it is recommended to identify a small set of the most appropriate indicators to estimate stream health. Identifying a small set of relevant indicators will:

- Generalize an approach for characterizing flow alteration,
- Minimize statistical redundancy and computational effort, and
- Facilitate to obtain optimal solutions (Gao, Vogel et al. 2009).

This chapter describes the identification of ecologically relevant indicators (among several available hydrologic indicators) required for estimating stream health.

Using IHA Indicators

IHA generates a total of 67 hydrologic indicators in two groups. The first group, containing 33 indicators, is referred to as IHA-parameters, while the other group containing, 34 indicators, are considered Environmental Flow Components (EFC). All the IHA-parameters are used for estimating stream health in the Dundee Hydrologic Regime Assessment Method (DHRAM). Users need to only select the 33 IHA parameters if they use IHA-DHRAM approach to estimate stream health.

Using NATHAT Indicators

NATHAT software generates 171 hydrologic indicators. Although all the parameters describe anthropogenic alterations to stream health, many parameters also convey overlapping information. Therefore, it is recommended to select the most appropriate indicators. Selection of the most appropriate indicators is based on the following procedure (Figure 8.1). Each step of the procedure is discussed in further detail in this chapter.

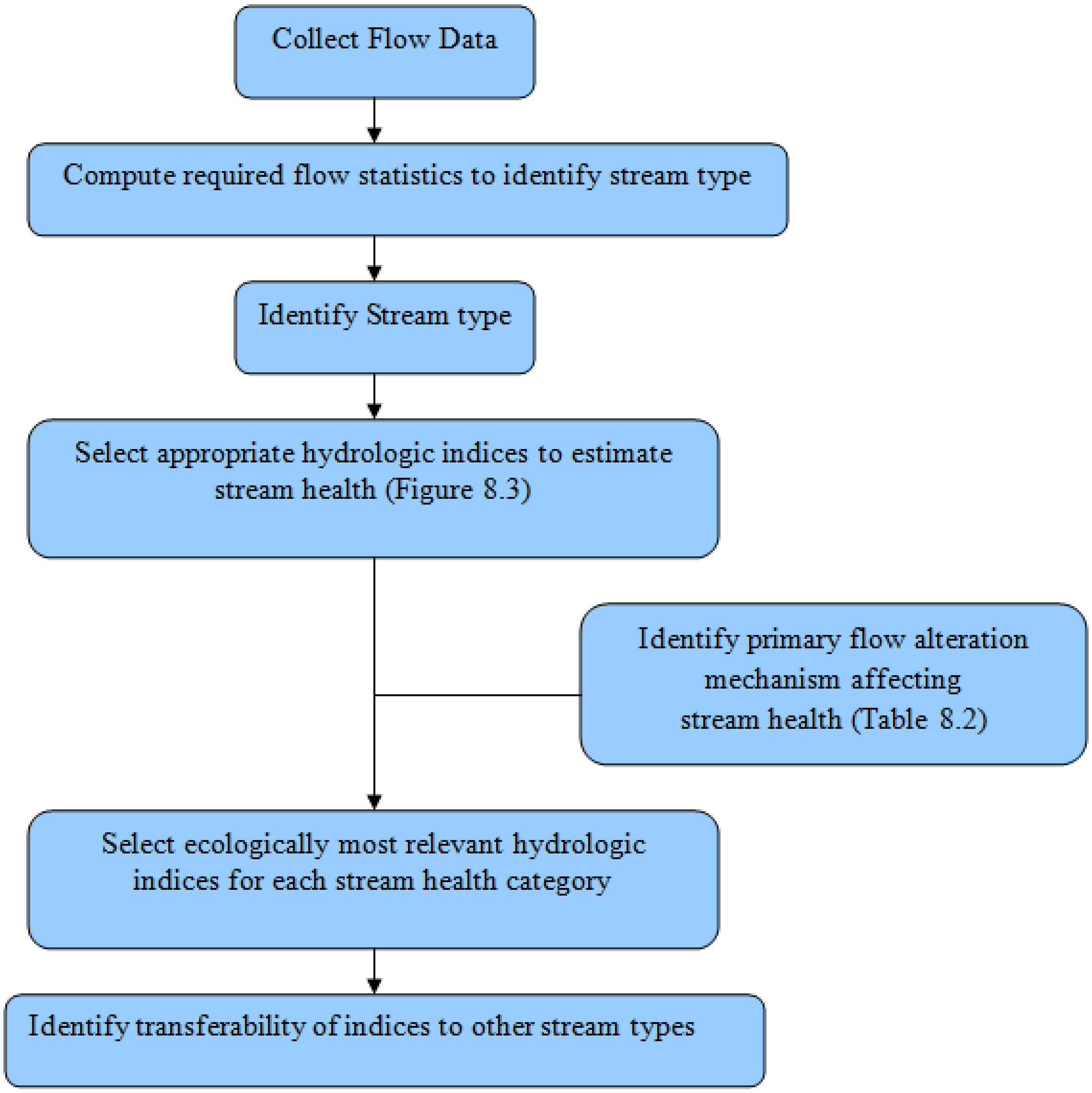

Figure 8.1: Protocols for Selection of NATHAT Indicators

Statistics Required for Estimation of Stream Type

Estimating stream type requires a few statistical parameters on mean daily flow data. They are listed in Table 8.1. The NATHAT program itself can estimate most of these parameters. For other indicators, the method used to estimate them is also shown in Table 8.1.

Table 8.1: Flow Statistics Required for Estimation of Stream Type

Flow Statistic (Unit)	Definition	Estimation
ZERODAY (days)	Number of days having zero discharge	NATHAT index D_L18
DAYCV (%)	Overall variability of mean daily flow	100 x (Standard deviation/mean) (NATHAT index M_A3)
DAYPRED (%)	Degree to which flow values are predicted and the duration	NATHAT index T_A2
FLDFREQ (yr^{-1})	Number of bank-full discharge events	No. of floods with magnitude > 1.67 year frequency flood
FLDDUUR (days)	Number of days above flood threshold#	NATHAT index D_H23
FLDPRED ()*	Maximum portion of flood in any six 60-day seasonal window	NATHAT index T_A3
FLDTIME (day)	Timing of flood onset	Beginning of 60 day period with highest FLDPRED
FLDFREE ()*	No flood period (or Flood free days)	Number of no flood days / 365 (NATHAT index D_H24)
LOWPRED ()*	Seasonal predictability of low flow	NATHAT index T_L3
LOWFREE ()*	Seasonal predictability of non-low flow	NATHAT index T_L4
BFI (%)	Base flow index (flow stability and chances of stream drying)	NATHAT index D_L15
* Unit-less and dimensionless parameter		# flood is defined as the magnitude of flow with 1.67 year return period

Estimate Stream Type

After generating NATHAT flow statistics (Table 8.1) stream type estimation follows the stepwise procedure outlined in Figure 8.2. The procedure identifies 11 different stream types based on various characteristics. There are four screening levels used to identify major stream types such as intermittent, snowmelt, groundwater, and perennial streams. Within the major stream type there are sub-classifications (Figure 8.2). The four levels of screening are based on:

1) Number of zero flow days (ZERODAY),
2) Variability (DAYCV), frequency (FLDFREQ) and duration (LOWFREE) of daily flows,
3) Predictability (FLDPRED) and duration (FLDDUR) of floods, and
4) Base flow index (BFI).

Not all the parameters listed in Table 8.1 are needed for stream type estimation. For some stream types, the number of parameters could be fewer. For example, an intermittent runoff stream could be identified by estimating just four parameters: ZERODAY, DAYCV, FLDFREQ and LOWFREE.

Select Appropriate Hydrologic Indices Based on Stream Type

Olden and Poff examined 171 NATHAT indicators (from 13 publications) using a “principal component analysis” to identify the non-redundant and most informative hydrologic indicators under each stream type (Olden and Poff 2003). Principal component analysis is a method to identify uncorrelated variables (principal components) from a list of many variables, most of them, are possibly inter-correlated. They used flow data from USGS for 420 sites across the entire United States. The flow data for this analysis were collected from sites with drainage area $\leq 5000\ km^2$ having little or no urbanization, no flow regulation and good quality flow data. For their study, they analyzed a 171 x 171 combination of hydrologic indices to identify the appropriate hydrologic indices under each stream type. The results of their analysis are presented in Table 8.2, which should be used as a guideline to select the suitable indices that should be used for estimating stream health given a stream type.

Figure 8.2: Estimation of Stream Type

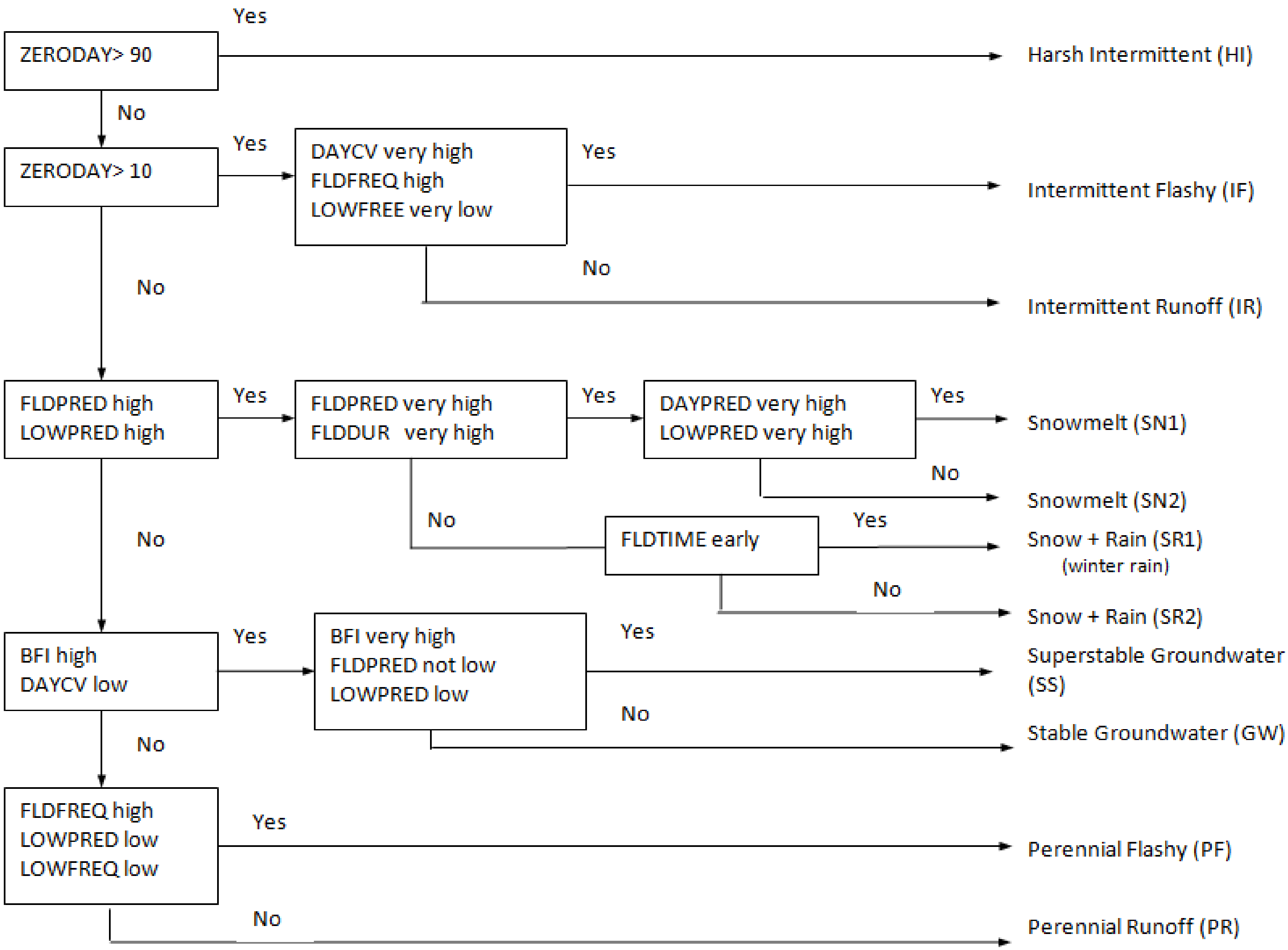

Table 8.2: Estimation of Stream Type

Flow component	Stream classification						All streams
	Intermittent		Perennial				
	Harsh intermittent	Intermittent flashy or runoff	Snowmelt	Snow and rain	Superstable or stable groundwater	Perennial flashy or runoff	
Magnitude of flow events							
Average flow conditions	$\mathbf{M_A34}$, $\mathbf{M_A22}$, $\mathbf{M_A16}$	M_A37, $\mathbf{M_A18}$, $\mathbf{M_A21}$, M_A9	$\mathbf{M_A29}$, M_A40	M_A3, M_A44	M_A3, M_A41, M_A8	$\mathbf{M_A26}$, M_A41, M_A10	M_A5, M_A41, M_A3, M_A11
Low flow conditions	M_L13, M_L15, M_L1	M_L16, M_L6, M_L22, M_L15	M_L13, M_L22	M_L13, M_L14	$\mathbf{M_L18}$, M_L14, M_L16	$\mathbf{M_L17}$, M_L14, M_L16	$\mathbf{M_L17}$, M_L4, M_L21, M_L18
High flow conditions	M_H23, M_H14, M_H9	M_H23, M_H4, M_H14, M_H7	M_H1, M_H20	M_H17, M_H20	M_H17, M_H19, M_H10	M_H23, M_H8, M_H14	M_H16, M_H8, M_H10, M_H14
Frequency of flow events							
Low flow conditions	$\mathbf{F_L2}$, F_L3, $\mathbf{F_L1}$	F_L3, $\mathbf{F_L2}$, $\mathbf{F_L1}$	F_L3, $\mathbf{F_L2}$	F_L3, $\mathbf{F_L2}$	F_L3, $\mathbf{F_L1}$, $\mathbf{F_L2}$	F_L3, $\mathbf{F_L2}$, F_L3	F_L3, $\mathbf{F_L2}$, F_L3, $\mathbf{F_L1}$
High flow conditions	$\mathbf{F_H2}$, F_H5, F_H7	F_H3, F_H7, $\mathbf{F_H2}$, F_H10	F_H8, F_H11	F_H3, F_H5	F_H3, F_H6, F_H11	F_H4, F_H6, F_H7	F_H3, F_H6, F_H7, $\mathbf{F_H2}$
Duration of flow events							
Low flow conditions	D_L13, $\mathbf{D_L1}$, $\mathbf{D_L2}$	$\mathbf{D_L18}$, $\mathbf{D_L16}$, D_L13, $\mathbf{D_L1}$	$\mathbf{D_L5}$, $\mathbf{D_L16}$	$\mathbf{D_L6}$, D_L13	$\mathbf{D_L9}$, D_L11, $\mathbf{D_L16}$	$\mathbf{D_L10}$, $\mathbf{D_L17}$, $\mathbf{D_L6}$	$\mathbf{D_L18}$, $\mathbf{D_L17}$, $\mathbf{D_L16}$, D_L13
High flow conditions	$\mathbf{D_H10}$, $\mathbf{D_H5}$, D_H22	D_H13, $\mathbf{D_H15}$, D_H12, D_H23	D_H19, $\mathbf{D_H16}$	D_H12, D_H24	D_H11, D_H20, $\mathbf{D_H15}$	D_H13, $\mathbf{D_H16}$, D_H24	D_H13, $\mathbf{D_H16}$, D_H20, $\mathbf{D_H15}$
Timing of flow events	$\mathbf{T_H1}$, $\mathbf{T_L2}$, $\mathbf{T_H2}$	T_A1, T_A2, $\mathbf{T_L1}$, T_H3	T_A1, T_A3	T_A1, $\mathbf{T_L1}$	T_A1, $\mathbf{T_H1}$, $\mathbf{T_L2}$	T_A1, T_A3, T_H3	T_A1, T_H3, T_A1, $\mathbf{T_L2}$
Rate of change in flow events	$\mathbf{R_A4}$, $\mathbf{R_A1}$, R_A5	$\mathbf{R_A9}$, R_A6, R_A5, R_A7	$\mathbf{R_A1}$, $\mathbf{R_A8}$	$\mathbf{R_A9}$, $\mathbf{R_A8}$	$\mathbf{R_A9}$, $\mathbf{R_A8}$, R_A5	$\mathbf{R_A9}$, R_A7, R_A6	$\mathbf{R_A9}$, $\mathbf{R_A8}$, R_A6, R_A5

Identify Primary Flow Alteration Mechanism

Flow alterations affect some or all the components of stream health. Components of stream health include: riparian vegetation, aquatic species, macro invertebrates, and physical alterations to the channel. For example, riparian vegetation of a stream could be affected by the decrease in number of bank-full discharge days in a year. To identify the dominant flow alteration mechanisms affecting different components of stream health an extensive literature review is needed. Poff and Zimmerman completed a comprehensive review of 165 papers over the past 40 years and characterized flow alterations in terms of magnitude, frequency, duration, timing and rate of change and identified the ecological response in terms of changes in aquatic species and riparian vegetation (Poff and Zimmerman 2010b). The results of their analysis are presented in Table 8.3 and Table 8.4.

Select Most Appropriate Indices for Estimating each Stream Health Component

Identifying the most appropriate indices for estimating stream health involves the correct selection of indices for the stream type and identifying the primary flow alteration mechanisms. Together, stream type and the primary flow alteration mechanisms provide ways to estimate stream health. An example is given below. More details on this are discussed in the Plum Creek watershed case study presented in Appendix B. Plum Creek is identified as a perennial runoff stream (Table B3-Appendix B). From Table 8.2 we can identify the appropriate hydrologic indices (under perennial runoff stream) to be used for estimating stream health. For example, the high flow indices on frequency, suitable for estimating stream health are F_H4, F_H6 and F_H7. In Table 8.3 and Table 8.4, category flow frequency suggests there will be a) shift in riparian community, b) reduction in species richness, and c) increase in wood production if there is a reduction in frequency of peak flows. Therefore, estimating the possible changes to riparian vegetation in Plum Creek indices F_H4, F_H6 and F_H7 were selected as some of the most appropriate ones. The other appropriate indices were related to magnitude and duration of flow.

Table 8.3: Primary Flow Alteration Mechanisms and the Corresponding Ecological Responses Aquatic Species

Flow Component	Primary Flow Alteration	Ecological Response	No. of papers with Consistent Ecological Response	Total Number of Papers Analyzed
Magnitude	Loss of peak flows	Altered recruitment, failure of seedling establishment, terrestrialisation of flora, increased success of non-natives, lower species richness, vegetation encroachment into channels, increased riparian cover, altered assemblage	18	28
Frequency	Decreased frequency of peak flows	Shift in community composition, reduction in species richness, increase in wood production	4	4
Duration	Decreased duration of floodplain inundation	Reduced growth rate or mortality, altered assemblage, terrestrialisation or desertification of species composition, reduced area of riparian cover, increase in non-natives	13	18
Timing	Loss of seasonal flow peaks	Reduced riparian plant recruitment, invasion of exotic plant species, reduced plant growth and increased mortality, reduction in species richness and plant cover	4	4
Rate of change	Increased variability	Decreased germination survival and growth of plants, decreased abundance and change in species assemblage of water birds	2	2

Table 8.4: Primary Flow Alteration Mechanisms and the Corresponding Ecological Responses-Riparian Vegetation

Flow Component	Primary Flow Alteration	Ecological Response	No. of papers with Consistent Ecological Response	Total Number of Papers Analyzed
Magnitude	Loss of extreme high/low flows Greater magnitude of extreme high/low flows	Loss of sensitive species, altered assemblage, reduced diversity, increase in non-natives, life cycle disruption	66	71
Frequency	Decreased frequency of peak flows	Reduced and non-seasonal reproduction, reduced habitat for young fish, decreased species richness and abundance	8	12
Duration	Decreased duration of floodplain inundation	Decreased abundance of young fish, Change in juvenile fish assemblage, loss of floodplain specialists	4	7
Timing	Shifts in peak flow, increased predictability	Disruption of spawning cues, decreased reproduction, change in diversity	12	12

Use of Selected Hydrologic Indices with Other Streams

Although the appropriate hydrologic indices to estimate stream health were identified for specific stream types, there is some degree of transferability of indices to other streams (Table 8.5), (Olden and Poff 2003). Table 8.5 shows the correlation (of hydrologic indices) between different stream types. The correlation coefficients represent the applicability of indices developed for one stream type relative to other streams. A correlation coefficient of one represents a relationship which is perfectly correlated and zero means they are uncorrelated. Note that the indices are becoming less applicable as the stream to be analyzed becomes flashy/intermittent. If a correlation coefficient of 0.75 or higher is acceptable, then it is evident that the hydrologic indices chosen for a perennial stream could be reliably used to estimate the health of all the streams except Harsh Intermittent. In other words, the indices chosen for a perennial stream could be applicable for super-stable, stable groundwater stream, for snow and rain dominated, intermittent flashy, runoff and harsh intermittent streams with correlation coefficients of 0.939, 0.913, 0.815, 0.771, and 0.492, respectively.

Table 8.5: Transferability of Ecologically Relevant Hydrologic Indices, taken from (Olden and Poff 2003)

	Harsh Intermittent	Intermittent flashy or runoff	Snowmelt	Snow and rain	Superstable or stable groundwater	Perennial flashy or runoff	All streams
Harsh Intermittent	----						
Intermittent flashy or runoff	0.542	----					
Snowmelt	0.274	0.556	----				
Snow and rain	0.417	0.630	0.905	----			
Superstable/stable groundwater	0.488	0.694	0.742	0.860	----		
Perennial flashy or runoff	0.537	0.754	0.777	0.861	0.912	----	
All streams	0.492	0.771	0.815	0.913	0.939	0.965	

Chapter 9: Step 7 – Identify and Classify Stream Health Impacts

To estimate stream health and to identify the extent of stream impairment, the Dundee Hydrological Regime Assessment Method (DHRAM) (Black, Rowan et al. 2005) is used as a framework in this assessment protocol. DHRAM scoring method is designed for use with ecologically relevant hydrologic indicators generated by IHA software. However, it can also be used with similar hydrologic indicators generated by other software programs. DHRAM links hydrologic indicators to ecological impact through the concept of risk under the assumption that risk to stream health increases in direct proportion to the total alteration to the hydrologic regime (or flow magnitude and pattern). The final output is a DHRAM classification between one (no impact to stream health) and five (severe impact to stream health). Although the scoring system was designed for rivers in Scotland, it is equally applicable for rivers in other countries where the required flow data is available (Black, Rowan et al. 2005).

The procedure for using the DHRAM approach to estimate stream health is presented in Figure 9.1. A detailed discussion of each step is presented in the following sections.

Hydrologic Indicators

DHRAM uses 32 hydrologic indicators (Table 9.1). They are divided into 5 groups of equal importance. Groups one to five indicate:

- Magnitude of monthly flows,
- Magnitude and duration of annual extreme flows,
- Timing of annual extreme flows,
- Frequency and duration of high and low flows, and
- Rate and frequency of change in flow conditions.

Each group of indicators has some ecological relevance that relates to stream health (Richter, Baumgartner et al. 1996; Poff and Zimmerman 2010b). For example, group one indicators are related to ‘habitat availability for aquatic organisms’. Groups two, three, four and five (Table 9.1) relate to structuring of river channel morphology, the physical habitat conditions, compatibility with life cycles of organisms, frequency and duration of anaerobic stress for plants, and entrapment on islands and floodplains respectively.

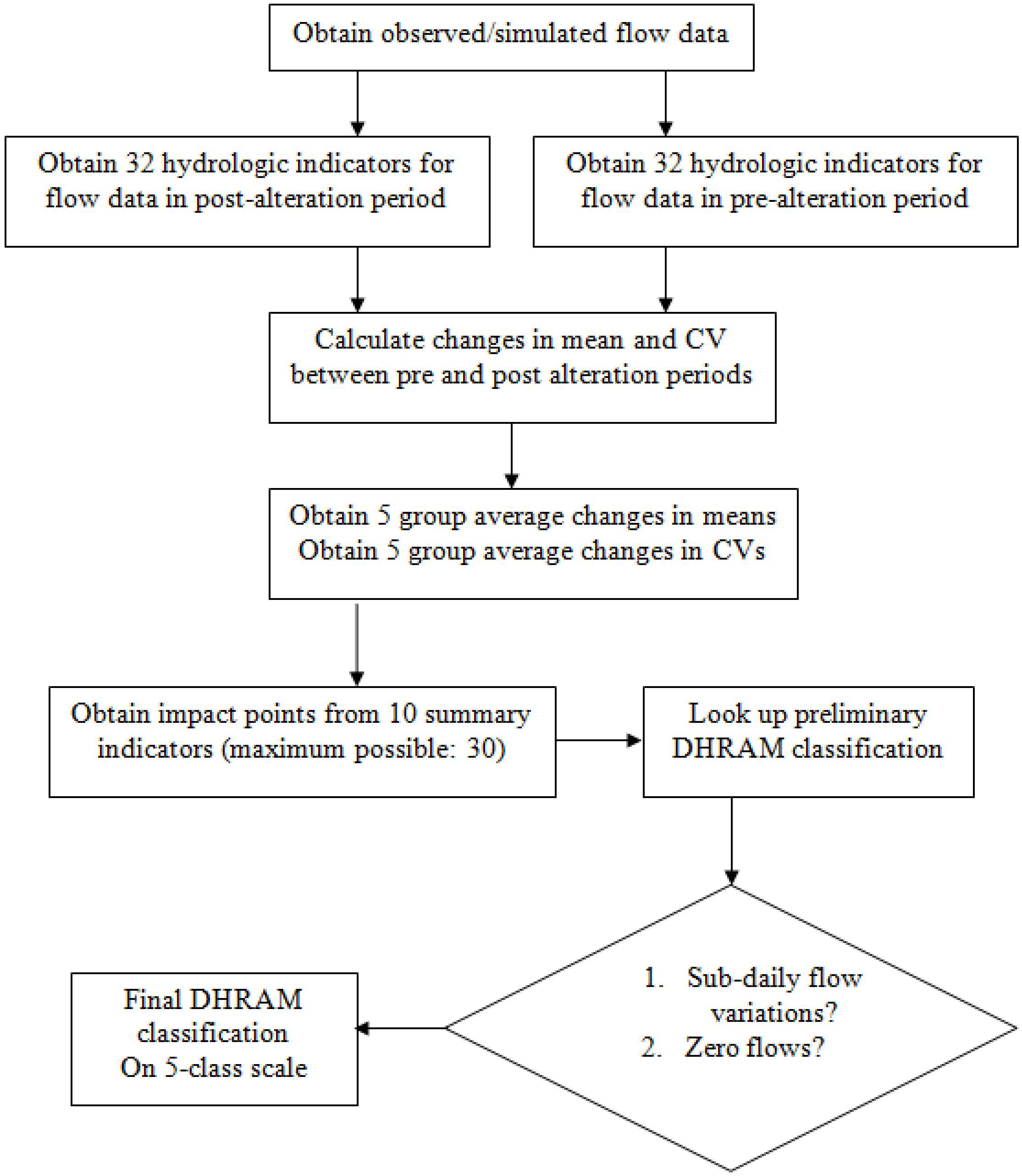

Figure 9.1: Method for Estimating Stream Health using DHRAM Approach (Black, Rowan et al. 2005)

Therefore, by quantitatively analyzing the difference in values of these indicators during pre- and post-alteration periods we can judge the health of the stream. It should be noted that means and coefficients of variation (CVs) are estimated for each parameter in each group.

$$CV = \frac{\text{Standard Deviation}}{\text{Mean}}$$

Table 9.1: Ecologically Relevant Hydrologic Indicators in the IHA Method (Black, Rowan et al. 2005)

Group 1. Magnitude of monthly water conditions Example of ecological relevance: habitat availability for aquatic organisms Mean January flow Mean February flow Mean March flow Mean April flow Mean May flow Mean June flow Mean July flow Mean August flow Mean September flow Mean October flow Mean November flow Mean December flow
Group 2. Magnitude and duration of annual extremes Example of ecological relevance: structuring of river channel morphology and physical 1-day-minimum flow 1-day-maximum flow 3-day-minimum flow 3-day-maximum flow 7-day-minimum flow 7-day-maximum flow 30-day-minimum flow 30-day-maximum flow 90-day-minimum flow 90-day-maximum flow
Group 3. Timing of annual extremes Example of ecological relevance: compatibility with life cycles of organisms

Date of 1-day maximum flow

Date of 1-day-minimum flow

Group 4. Frequency and duration of high and low pulses

Example of ecological relevance: frequency and duration of anaerobic stress for plants

Annual number of high pulses

Annual number of low pulses

Mean duration of high pulses (days)

Mean duration of low pulses (days)

Group 5. Rate and frequency of change in conditions

Example of ecological relevance: entrapment on islands and floodplains

Mean daily flow increase

Mean daily flow decrease

Number of rises

Number of falls

Analyze Hydrologic Indicators

IHA software generates annual indicators. Hence, the annual IHA indicators must be averaged for the entire period of record (say entire pre-alteration period or post-alteration period) to ascertain differences between pre- and post-alterations. For example if the pre-alteration period has ten years of record, IHA will produce ten different values for Mean January flow (group one parameter). An average of those ten values is needed to calculate the mean January flow for the entire pre-alteration period. In a similar fashion, mean January flow need to be estimated for the post-alteration period. The next step is to estimate the percentage difference between pre- and post-alteration values. It is estimated as:

$$\text{\% difference in parameters} = \frac{(\text{Post} - \text{Alteration Value}) - (\text{Pre} - \text{Alteration Value})}{(\text{Pre} - \text{Alteration Value})} \times 100$$

The percentage difference is estimated separately for means and coefficients of variation (CVs) and is summarized for each group (Table 9.2). The percentage difference provides an estimate of the impact points, which are eventually used to estimate stream health.

Table 9.2: Hydrologic Alteration Limits used for Allocation of Impact Points (Black, Rowan et al. 2005)

Index	IHA-Summary Indicator	% change in group score		
		Lower threshold (1 impact point)	Intermediate threshold (2 impact points)	Upper threshold (3 impact points)
1a	Group 1 means	19.9	43.7	67.5
1b	Group 1 CVs	29.4	97.6	165.7
2a	Group 2 means	42.9	88.2	133.4
2b	Group 2 CVs	84.5	122.7	160.8
3a	Group 3 means	7.0	21.2	35.5
3b	Group 3 CVs	33.4	50.3	67.3
4a	Group 4 means	36.4	65.1	93.8
4b	Group 4 CVs	30.5	76.1	121.6
5a	Group 5 means	46.0	82.7	119.4
5b	Group 5 CVs	49.1	79.9	110.6

Estimate Impact Points

Following calculation of average percentage differences for means and CVs for each group, the values are assigned with impact points using Table 9.2. The information presented in Table 9.2 is based on known information on stream health for watersheds of varying sizes and hydrologic pattern (Black, Rowan et al. 2005). When using the DHRAM approach, Table 9.2 should always be referred to for assigning impact points to the percentage differences. For example, if the percentage difference for means in group one is 25, that will receive two impact points because it is more than 19.9 and less than 43.7 (Table 9.2). In a similar way, impact points have to be estimated for means and CVs for all the five groups. For any stream, there will be a maximum of ten categories (five groups and two categories in each group) to assign impact points. Each category has a maximum of three impact points. Therefore, the maximum possible total impact point is 30.

Estimate Stream Health

Once the total impact point for all the groups is obtained, it has to be categorized into one of the five possible classes of stream health conditions using Table 9.3. After categorizing the stream into one of the five health classes, it can be downgraded by one class if the anthropogenic changes alter sub-daily flow (if analyzed) by 25% for the flow magnitude that has a 95% frequency of occurrence or if the stream dries out as a result of anthropogenic changes. More details on using DHRAM method for estimation of stream health are discussed using case examples in Appendices B and C, respectively. Estimation of stream health using the NATHAT-DHRAM method and the IHA-DHRAM method are described in Appendices B and C, respectively.

Table 9.3: DHRAM Classification of Stream Health Impacts (Black, Rowan et al. 2005)

Class	Points range	Description
1	0	No risk to stream health
2	1-4	Low risk to stream health
3	5-10	Moderate risk to stream health
4	11-20	High risk to stream health
5	21-30	Severe risk to stream health

Note: The classification is dropped (move down in the table) by one if anthropogenic sub-daily flow changes exceed 25% of the 95% flow frequency, and/or the classification is provisionally dropped by one class if no flow occurs as a result of anthropogenic activities, and Class five is the lowest classification that can be allocated.

Chapter 10: Step 8 – Estimate Overall Stream Health

This chapter outlines methods for estimating stream health using a time series of mean daily flow data. Three different methods are explored. The first method uses the concept of eco-deficit versus eco-surplus using flow duration curves to estimate the presence or absence of a stream health problem. The second method uses IHA-DHRAM framework to estimate the overall health of a stream, and the last method uses NATHAT-DHRAM approach to provide a detailed estimation of stream health including its components. All the three methods are described with case examples (in Appendices B and C).

Eco-Deficit and Eco-Surplus Method Using Flow Duration Curves (FDCs)

The method of developing FDCs is outlined in Chapter 7. Stream flow varies over several orders of magnitude. Therefore, analyzing flow data and identifying hydrologic changes and their impacts on stream health is not an easy task. FDCs provide a graphical illustration of the overall hydrologic state of a river system (Vogel, Sieber et al. 2007).

Having the FDCs for pre- and post-alteration conditions we need a simple and efficient way to estimate stream health. The concept of the Eco-deficit and Eco-surplus method (originally developed for regulating flows through dams in an ecologically sustainable way) offers a simplified graphical representation of hydrologic impacts using FDCs. The user can visualize the hydrologic changes and easily interpret the impacts of those hydrologic changes on stream health. It should be noted that this metric alone is insufficient to adequately capture all the hydrologic changes because, the hydrologic variations occur in terms of magnitude, timing, duration, frequency and rate of change. In this approach, timing and seasonality can be addressed to some extent because the eco-deficit and eco-surplus can be computed over any time period of interest (monthly, annual or seasonal) and reflect the overall changes in stream flow (Vogel, Sieber et al. 2007). Therefore, the eco-deficit and eco-surplus concept seems to be an excellent tool for interpretation of the overall hydrologic changes and for making a preliminary judgment on stream health.

Figure 10.1 shows a FDC for the Plum Creek Watershed during pre- and post-alteration scenarios. A dashed curve illustrates the FDC for the Plum Creek during unaltered or pre-land cover change conditions. The solid curve represents the FDC for the Plum Creek during post-alteration (or post-land cover change) conditions. Both curves represent the cumulative of stream flows. The hatched area between the solid curve and dashed curve is called eco-surplus. It represents the net volume of water that is now available in excess of pre-alteration conditions due to the impacts of land cover change and urbanization in the Plum Creek Watershed.

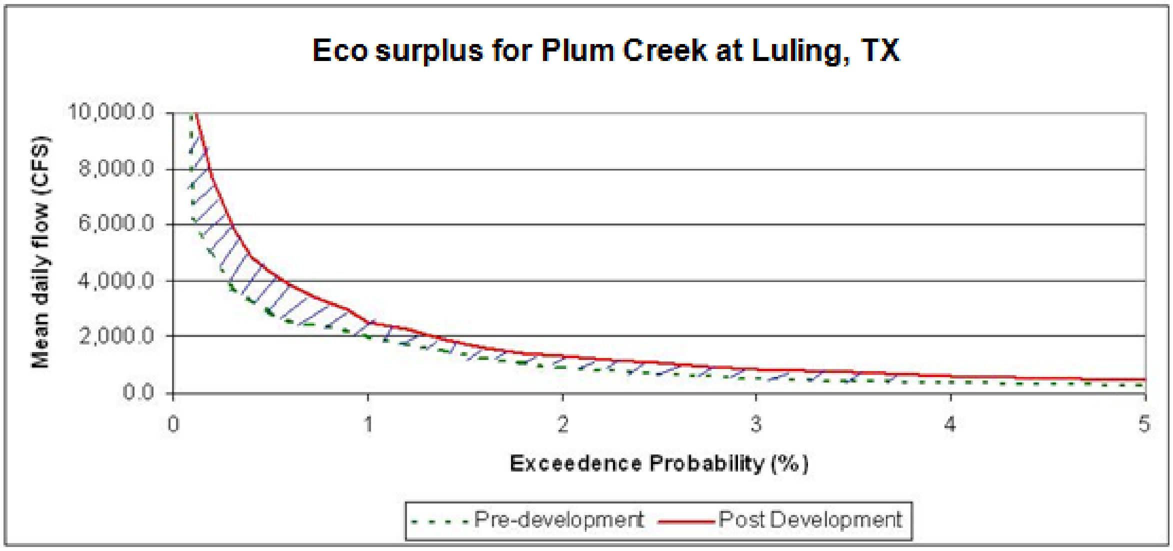

Figure 10.1: Eco-Surplus in High Flow Portion of FDC

The opposite is called eco-deficit. The general connotation is that the eco-deficit is harmful to stream health and eco-surplus is not. It should be noted that the ecosystems depend upon both high and low flows for optimal health. Any change in the natural flow regime, whether higher or lower, can impair stream health depending on magnitude, timing, duration, frequency and rate of change (Poff and Zimmerman 2010b). In the Plum Creek Watershed example presented here, there is eco-surplus in both high flows (Figure 10.1) and low flows (Figure 10.2).

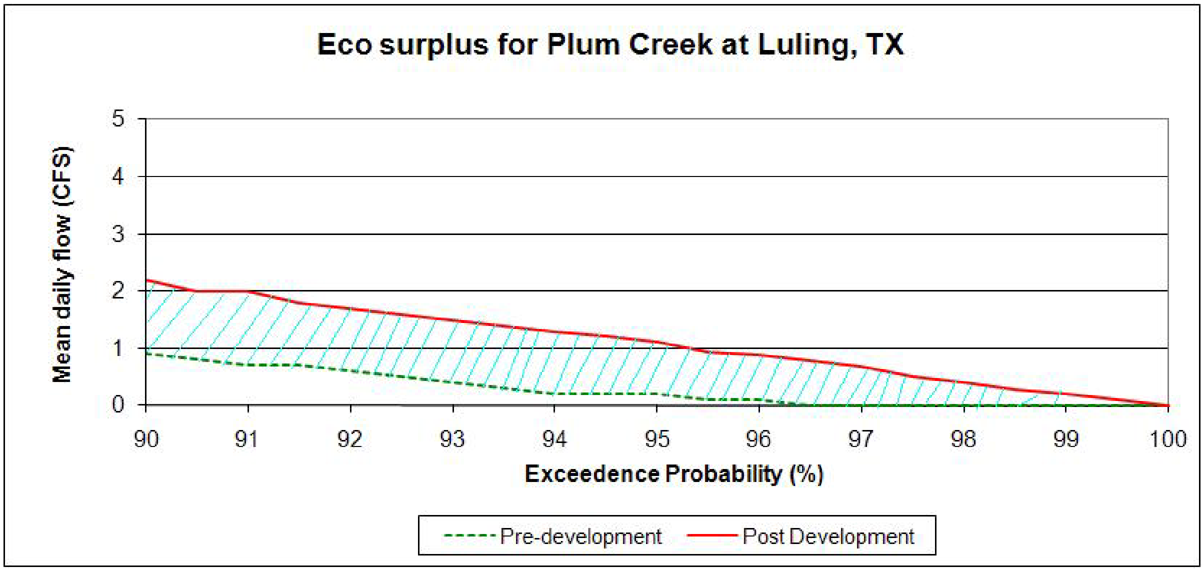

Figure 10.2: Eco-Surplus in Low Flow Portion of FDC

The eco-surplus in low flows may not impair stream health because during post-land cover change the stream is less likely to dry out (Figure 10.2). However, during high flows the eco-surplus in Plum Creek is likely to impact stream health because the magnitude of eco-surplus is high. For example, 6,000 ft^3/sec of flow occurred with a certain exceedance probability during pre-land cover change. For the same probability, post-land cover change shows a flow rate of 10,000 ft^3/sec, (a change of greater than 50% in magnitude). In another example, a flow rate of 5,000 ft^3/sec occurred with a certain exceedance probability during pre-land cover change. For the same probability, post-land cover change shows a rate of flow of 8,000 ft^3/sec (again a change of greater than 50% in magnitude). This could also be interpreted in terms of change in frequency. For example, a rate of flow of 2,000 ft^3/sec during pre-land cover change occurred with a probability of 1% exceedance. However, the same flow during post-land cover change occurred with a probability of 1.4% meaning the high flows are becoming more frequent. These changes could have affected the stream health. As a part of this study, some guidelines were prepared to estimate the impacts on stream health based on the extent of occurrences of eco-surplus and eco-deficit (by visual interpretation) (Table 10.1). In Table 10.1, D refers to eco-deficit and S refers to eco-surplus.

Table 10.1: Estimating Stream Health by Interpreting Eco-Deficit and Eco-Surplus Information of Flow Duration Curves (D–Deficit and S-Surplus)

Possible Scenarios	High flow portion (head) of FDC		Low flow portion (tail) of FDC		Stream Health Problems
	Eco-Surplus	Eco-Deficit	Eco-Surplus	Eco-Deficit	
SS	Small		Small		No or minimal
SS	Big		Big		Minimal to moderate
SD	Small			Small	Minimal
SD	Big			Big	Moderate to High
DD		Small		Small	Minimal
DD		Big		Big	Moderate to High
DS		Small	Small		No or minimal
DS		Big	Big		Moderate to High

The method of estimating stream health using eco-deficit – eco-surplus follows the steps outlined in Figure 10.3.

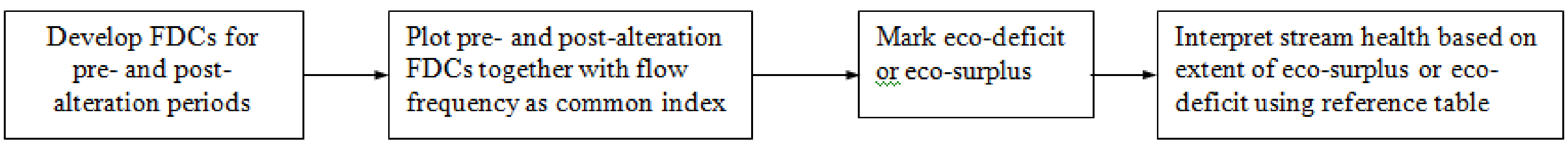

Figure 10.3: Estimation of preliminary stream health information using FDCs

Identification of a hydrologic alteration in flow data and separation of that flow data into pre- and post-alteration periods are essential requirements of using this approach. Then FDCs have to be prepared for pre- and post-alteration conditions. Using probability of exceedance or frequency of stream flow as a common index (X-axis), FDCs for both pre- and post-alteration conditions should be plotted together. The difference between the two FDCs should be marked clearly and identified as eco-deficit or eco-surplus. The eco-surplus or eco-deficit obtained should be interpreted for stream health conditions using Table 10.1 as the reference.

Estimate Stream Health Using IHA-DHRAM Approach

IHA-DHRAM approach estimates overall health of a stream although a certain combination of parameters could identify the status of a particular stream health component (say group one affects habitat availability for aquatic organisms). The IHA-DHRAM approach is simple, straight forward and easy to follow. The stepwise procedure involved is shown in Figure 10.4.

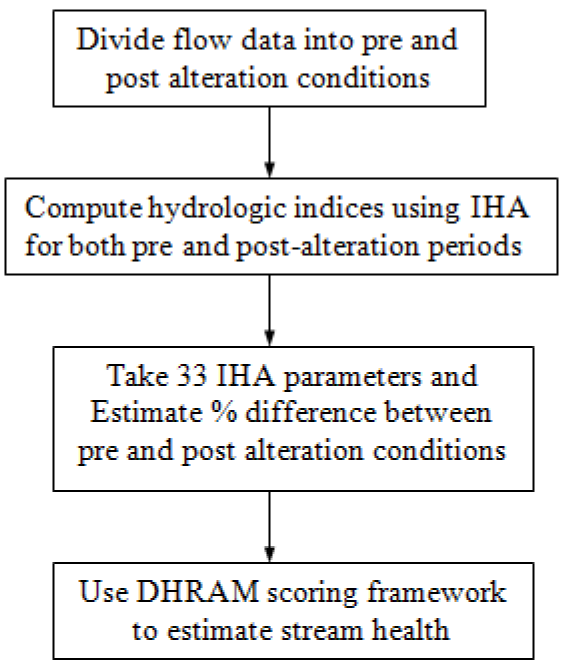

Figure 10.4: Procedure to Estimate Stream Health using IHA-DHRAM Approach

Obtaining flow data (see Chapter 4) and separating it into pre- and post-alteration periods (see Chapter 5) are essential requirements to use the procedure. Then the 33-IHA parameters (see Chapter 6) need to be estimated for both pre- and post-alteration using the IHA software. The next step involves taking the percentage difference in indicator values between pre- and post-alteration scenarios. This has to be estimated for each group of parameters (see Chapter 9). The final step is to score the percentage differences and make a classification of stream health using DHRAM scoring framework. More details on this approach are described in Appendix C using the White Rock Creek case example. More details on each step involved in using IHA-DHRAM approach are outlined in the previous chapters of this report.

Estimate Stream Health Using NATHAT-DHRAM Approach

A more detailed estimation of stream health is possible using the NATHAT-DHRAM approach. For example it is possible to identify the health of riparian vegetation or aquatic species using this approach. The stepwise procedure involved is shown in Figure 10.5.

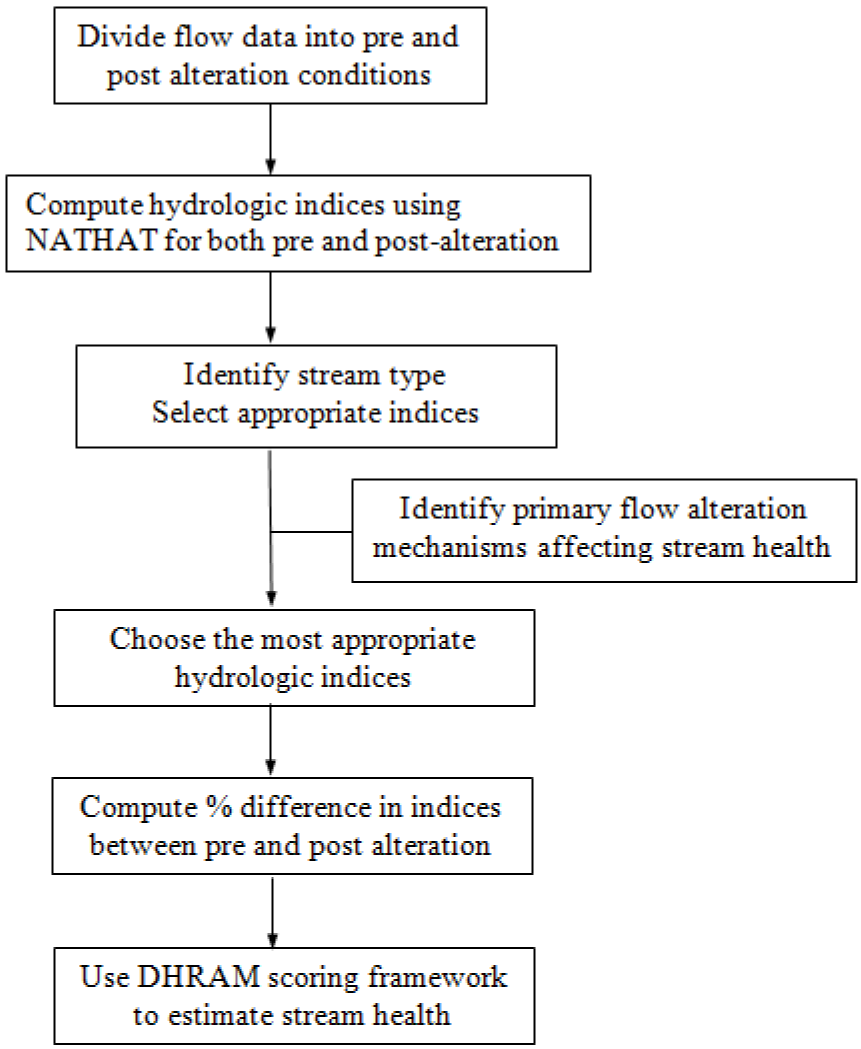

Figure 10.5: Procedure to Estimate Stream Health Using NATHAT-DHRAM Approach

Obtaining flow data (Chapter 4) and separating it into pre- and post-alteration periods (Chapter 5) are essential requirements to use this procedure. The next step involves generation of all the NATHAT indices (Chapter 6) for both pre- and post-alteration using the NATHAT software. The next steps involve identification of stream type (Chapter 8), identification of primary flow alteration mechanisms (Chapter 8) and prioritizing the most appropriate indices to be used for estimation of stream health (Chapter 8). After that, taking the percentage difference in indicator values between pre- and post-alteration scenarios comes next. This has to be estimated for each component for stream health (Chapter 9), for example, for riparian vegetation. The final step is to score the percentage differences and make a classification of stream health using DHRAM scoring framework. Additional details on this approach are described in Appendix B using the Plum Creek case example. More details on each step involved in using NATHAT-DHRAM approach are outlined in the previous chapters of this report.

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